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Effects of Early and Late Rest Intervals on Performance and Consolidation of a Keyboard Sequence

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Effects of Early and Late Rest Intervals on Performance and Consolidation of a Keyboard Sequence

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Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

May 2007

Acknowledgements

I wish to express my sincere appreciation to the members of my committee for their teaching, inspiration, and continued support during my studies at The University of Texas at Austin. A special thank-you to my major advisor, Dr. Robert A. Duke, for his guidance and steadfast encouragement over the last 5 years.

Effects of Early and Late Rest Intervals on Performance and Consolidation of a Keyboard Sequence

Publication No._____________

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The University of Texas at Austin, 2007

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I designed two experiments to study the extent to which 5-minute rest intervals placed early and late during practice influence motor sequence learning. In Experiment 1, 26 nonmusicians practiced a 5-note sequence with their left (non-dominant) hand on a digital piano, repeating the sequence "as quickly and accurately as possible" during 6 30-second practice blocks alternating with 30-second pauses. The training sessions for half the participants included an extended rest interval of 5 minutes between Blocks 3 and 4. Following a night of sleep, all participants performed the sequence in 6 30-second blocks with a 5-minute rest interval between Blocks 3 and 4. I found no significant differences attributable to rest condition in the number of correct key presses per block (CKP/B) during training or retest.

In Experiment 2, 36 nonmusicians performed the same 5-note sequence over 12 30-second blocks alternating with 30-second pauses. One group (*N* = 12) rested for 5-minutes between Blocks 3 and 4 (early rest); another group (*N* = 12) between Blocks 9

and 10 (late rest); and a control group (N = 12) performed the 12 blocks without an extended rest interval. All were retested following a night of sleep in a procedure identical to the retest in Experiment 1.

The introduction of extended rest in the early and late stages of practice significantly affected the rates of learning within and between sessions. Immediately following the 5-minute rest intervals, participants showed large gains in CKP/B, but only following the early rest did participants continue to show large gains across the next two blocks of practice. Participants in the early rest group also showed the largest overnight gains between training and retest. These findings suggest that neurophysical processes that occur during 5-minute rest intervals enhance performance and that the temporal placement of rest in a training session affects subsequent motor sequence learning and the consolidation of procedural memories.

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Chapter 1: Introduction

Understanding the process by which humans learn has long been a key objective for researchers in psychology, kinesiology, the neurosciences, and education. Though the process of learning is multifaceted, studying behavior can be a first step in fully characterizing how humans acquire knowledge. In music, the development of skill is of utmost importance to the success of performers, who strive for refined motor movements through efficient practice techniques. Extant findings across learning domains undoubtedly have important implications for understanding the ways in which musicians acquire skills. Reciprocally, the study of behavior in music learning offers valuable data that may help to enhance the current understanding of human learning.

HUMAN LEARNING

Learning is commonly recognized as the acquisition, refinement, and retention of knowledge or skills. The definition of learning from the perspective of neurophysiology extends further, since the components of learning rely on experience-dependent plasticity of the brain that mediates behavioral changes associated with learning. The observable effects of learning—the ability to recite a memorized poem, to type faster, or to execute a more even-sounding arpeggio on the piano—are the bases of assessments of current knowledge or ability. What happens behaviorally also provides a window into the intricate developments that take place in a learner's brain and which ultimately are the foundation for learning.

When individuals learn, neural representations of new memory are created, transformed, and stored over time, creating a long-term representation of recent experiences. As a result, learned knowledge or skill may be recalled even after extended periods of time and without the need for relearning.

Of course, memories are not all alike. Declarative memories are recollections of information and experiences and can generally be expressed verbally. The declarative memory category includes semantic memories—recollections of information or fact—and episodic memories—recollections of past events. Recalling the title and composer of a musical work (semantic) and remembering details from a childhood recital (episodic) engage declarative memory processes.

Whereas declarative memory concerns the memories for *what* and *why*, procedural memory concerns *how* to do things. Walking, riding a bike, and playing a scale on a musical instrument involve procedural memory. Procedural memory is further divided into sub-classifications that include perceptual memory, which involves the analysis and interpretation of sensory experiences, and motor memory, which involves coordinated physical movement.

Distinctions between declarative and procedural memory extend beyond obvious behavioral differences. Each memory type calls on distinct brain areas for processing. For example, the hippocampus is involved in the formation of declarative memory (Eichenbaum, 2001; Tulving & Markowitsch, 1998); the cerebellum, basal ganglia, the frontal and parietal cortices, as well as supplementary motor areas and the primary motor cortex are involved during procedural learning (Doyon & Benali, 2005; Doyon et al., 2002; Penhune & Doyon, 2005; Petersen, van Mier, Fiez, & Raichle, 1998; van Mier et al., 2004). Although both declarative and procedural memories are enhanced by rehearsal, the retention, maintenance, and refinement of procedural memories usually requires extended periods of repetition.

Naturally, the acquisition and refinement of music performance skills constitute a prime example of procedural learning. Musicians' physical movements combine to produce tone quality, articulation, dynamic inflection, and all of the other variables that are associated with musical sound. As is true of skills in dance, sports, and other activities that depend primarily on physical movement and coordination, music skills are unattainable without practice. It is through repetition that skill acquisition and refinement are made possible. Over time, acquired skills become part of an elaborate repertoire of movements from which learners can regularly select in performance.

Repetition of procedural skills, including music skills, prompts modifications in the brain, and these changes are the foundation for improvements observable in performance. Thus, behavioral changes in performance observed during skill practice are only one indication of learning. The acquisition of any new knowledge requires cortical and cerebellar plasticity, which begins during physical practice and continues even in the absence of practice. Simply put, learning does not cease when active practice ends; instead, neurophysical changes in the brain begun as a result of skill repetition persist following active practice, and the learning process continues covertly.

During the hours following practice, newly formed skill memories are thought to transform from an initial, somewhat labile state to a more stable state that is less susceptible to interference, resulting in facilitated performance when skills are recalled at a later time. This “off-line” process is known as memory consolidation, and its effects have been observed in perceptual and motor skill performance, as well as in declarative learning.

When a learner rehearses new knowledge or skills, processes of protein synthesis cause physical changes in the synaptic structures of the brain. In turn, the creation and modification of connections among networks of neurons stabilize the representation of these memories. Memory consolidation involves both the reorganization of the neuronal connections that comprise new memories and the relocation of memory structures (Muellbacher et al., 2002; Walker, 2005). The behavioral outcome of these inward changes is the ability to recall learned skills.

Through the process of consolidation-based *stabilization*, which begins during initial practice and continues for up to 4 to 6 hours following practice, memories become increasingly resistant to interference from competing stimuli, and performance levels reached at the end of practice are maintained (Brashers-Krug, Shadmehr, & Bizzi, 1996; Shadmehr & Brashers-Krug, 1997; Shadmehr & Holcomb, 1997). Disruption of this process is observed when interference, in the form of trauma, injection of chemical agents, or competing behavioral tasks, is presented prior to the completion of consolidation-based stabilization (Bourtchouladze et al., 1998; Muellbacher et al., 2002; Trepel & Racine, 1999). When interfering stimuli are introduced 4 to 6 hours after the end of active practice, following the completion of wake-based consolidation, no decrements in memory are observed.

Memory consolidation facilitates not only the maintenance of skill memories, but also the enhancement of skill. Whereas wake-based consolidation serves primarily to maintain memory, processes that occur during post-practice sleep are thought to result in the consolidation-based *enhancement* of new skill memory (Gaab, Paetzold, Becker, Walker, & Schlaug, 2004; Kuriyama, Stickgold, & Walker, 2004; Stickgold & Walker, 2005; Walker, 2005; Walker, Brakefield, Hobson, & Stickgold, 2003; Walker, Brakefield, Seidman et al., 2003). The execution of recalled skills is generally quicker and more accurate when performed following periods of sleep. This phenomenon, which is found to occur during overnight sleep and during daytime naps of sufficient duration, is observed in both simple and complex perceptual and motor skills. Sleep-based consolidation effects are also observable in the behaviors of novices and more advanced learners (Duke & Davis, 2006; Simmons & Duke, 2006).

Despite extensive evidence supporting wake- and sleep-based consolidation hypotheses, there remain a number of inconsistencies regarding the behavioral effects of these phenomena. For example, wake-based consolidation is thought to stabilize memory; that is, maintain performance levels obtained by the end of practice. However, for certain types of procedural skills, namely auditory discrimination tasks and skills learned without conscious awareness, enhancements in performance are found to develop across waking hours (Atienza & Cantero, 2001; Robertson, Press, & Pascual-Leone, 2005; Robertson, Pascual-Leone, & Press, 2004; Roth, Kishon-Rabin, Hildesheimer, & Karni, 2005). In these cases, learners demonstrate performance improvements over periods of wake and over intervals of sleep.

In some instances, enhancements in performance are observed only moments after skill practice ends, prior to extended periods of consolidation. Intervals comprising minutes, during which learners rest from skill repetition, are significantly shorter than the time required for consolidation-based stabilization and enhancement processes to complete. Nevertheless, several studies report learners' improvements in skill performance following short rest intervals from practice. Hotermans and colleagues (2006), for example, show a "boost" in performance when practice resumes following a brief rest interval. Compared to learners who train on a sequential finger-tapping sequence for 28 blocks with intermittent 30-second pauses, which function to simply relieve fatigue, those who take a 5- or 30-minute break midway through training show significant improvements in performance immediately following the extended rest periods (Hotermans, Peigneux, Maertens de Noordhout, Moonen, & Maquet, 2006). Similar results have been observed in experimental music settings as well. During the acquisition of a simple sequence on a piano keyboard, learners' skills were significantly improved when practice resumed after a 5-minute rest interval (Davis, 2006). Likewise, musicians who practiced a 9-note keyboard sequence demonstrated enhancements in performance following 5-minute rest intervals (Simmons, 2007).

The potential for gains in performance just minutes after practice raises questions about the bases for such improvements. One key question is whether behavioral effects present after brief periods of rest are attributable to the same neurophysical processes that underlie changes in skill following more extended temporal intervals. In other words, can memory consolidation, thought to begin during practice but to progress over hours, "boost" performance after a span of minutes?

At first glance, performance enhancements following short rest intervals seem similar to sleep-based consolidation effects. In both cases, performance is considerably improved when skills are recalled, but enhancements following brief rest periods are usually short-lived, with performance levels returning to pre-rest levels during retesting (Eysenck & Frith, 1977; Hotermans et al., 2006). These temporary improvements, termed *reminiscence*, are unlike consolidation effects, which are reliably observed after longer intervals of rest and are sustained over extended periods of retesting. Thus, short periods of rest may be inadequate for the development of long-term behavioral change, but provide sufficient time for off-line processes to produce temporary effects.

Though improvements observed after brief rest periods are not permanent, they are indicative of neural processes and have implications for subsequent learning. In fact, Hotermans and colleagues (2006) report that improvements following 5 and 30 minutes of rest are comparable to skill enhancements observed after two nights of post-training sleep. This finding suggests that behavioral effects following short rest periods may predict the extent to which performance will improve following overnight memory consolidation processes. Yet, questions remain regarding the actual chain of neural events occurring immediately after practice and across subsequent minutes. What happens in the brain during 5 minutes of rest that influences a learner's performance once practice resumes? One suggestion is that reminiscence is simply the result of the elimination of inhibitory effects amassed during practice. In other words, the continued repetition of a skill over time, without the availability of rest, may in effect interfere with the potential for further skill improvement. Rest may allow for the elimination of these inhibitory effects, so that when repetition resumes, performance is improved. While the reminiscence hypothesis is plausible, it prompts further questions regarding the processes in action during the accrual and loss of practice-induced inhibition and the relationship of these processes to memory consolidation.

Despite the fact that brief periods of rest during practice are a common element of skill practice, the effects of brief rest on the process of motor sequence learning has yet to be fully characterized. In music, for example, learners often interrupt extended periods of practice with rest intervals comprising minutes to relieve physical or mental fatigue. Though commonly considered simply a break from a tiring activity, rest may do more than alleviate fatigue. Skill improvements following short breaks from practice may signify the processing of memory during rest (Hotermans et al., 2006). Systematic examination of the behavioral effects of brief rest periods on subsequent learning can lead to a better understanding of the neurological processes that continue when skill practice is interrupted.

MOTOR LEARNING IN MUSIC PERFORMANCE CONTEXTS

Motor learning is the basis of music performance skills. Thus, it may reasonable to assume that variables such as practice and rest also influence the learning of music skills. Unfortunately, the process by which motor memory develops through music practice and over periods of rest is rarely discussed in light of the current understanding of procedural learning. This is quite surprising given that the majority of professional musicians engage in extensive practice, during which time skills are modified and refined to achieve superior levels of performance.

Successful music making involves the planning and execution of countless motor movements. The goal of musicians, regardless of levels of expertise, is the refinement of these movements in the production of desired auditory effects. Skills inherent to music performance, like all motor skills, can only be acquired through practice. Researchers indeed acknowledge that musicians' practice centers on the modification of motor movements (Chaffin & Imreh, 2001; Chaffin, Imreh, Lemieux, & Chen, 2003; Miklaszewski, 1989), and that the learning of these movements facilitates the acquisition of a mental representation (i.e., an aural image) of the music being practiced (Chaffin et al., 2003; Miklaszewski, 1989). However, to date, music research fails to address how practice influences the neurological processes that underlie motor learning, and rather focuses on the strategies musicians use to improve technical and expressive aspects of performance. For example, when advanced pianists learn new repertoire, they initially work to develop the motor skills necessary to execute the technical demands of the piece. This stage of learning often involves the selection of combinations of fingering that often remains intact for the remainder of practice (Chaffin et al., 2003; Miklaszewski, 1989; Nielsen, 1999a). Chaffin and Imreh (2001) describe the significance of this careful approach in terms of the development of a course of motor movements that can be retained and recalled the same way in subsequent practice sessions. Researchers also report that professional musicians use the formal structure of a piece to guide practice, with starts and stops coinciding with the beginnings and ends of sections (Chaffin &

Imreh, 1997; Miklaszewski, 1989; Nielsen, 1999a; Williamon, Valentine, & Valentine, 2002). This, too, allows for motor movements to be encoded and easily retrieved from memory (Chaffin & Imreh, 1997).

Advanced musicians use several strategies to specifically address problem areas identified during practice. The most common of these includes the use of repetition. Musicians often employ an extensive routine of repeating targeted passages to ensure fluid technical execution (Maynard, 2006). Repeating material that has been isolated from a piece also functions to improve performance. Musicians often select small "chunks" of material to repeat (Chaffin & Imreh, 2001; Maynard, 2006; Miklaszewski, 1989; Nielsen, 1999a), which allows attention to be focused directly on problem areas without the distractions from surrounding material, subsequently easing cognitive load. Though musicians effectively use repetition in practice, younger players often fail to completely address errors when repeating selected material. When error correction is attempted, most developing musicians employ strategies that are insufficient and move on before problems are solved (McPherson & Renwick, 2001).

Other strategies used by musicians during practice include varying tempo in the repetition of material. Though purposefully selected, tempos are often not chosen in progressively increasing or decreasing order (Miklaszewski, 1989; Nielsen, 1999a). Alternation between fast and slow speeds, found advantageous for advanced musicians in acquiring and refining skills, is reported to be ineffective for less experienced musicians, however (Henley 2001). Breaking apart the physical movements involved in performance, such as playing hands separately in the case of piano practice, is found to be effective in the learning of new repertoire (Nielsen, 1999a, 1999b). Mental practice (e.g., imagining or picturing the execution of motor skills required by a passage) is also frequently implemented by musicians (Nielsen 1999a). The combination of physical and mental practice optimizes music learning according to Theiler and Lippman (1995), but the use of both physical and mental practice has yielded conflicting results in the literature. For instance, Rubin-Rabson (1941) suggests that combining physical and mental practice enhances performance more so than physical practice alone. Coffman (1990) reports that physical practice alone and the combination of physical and mental practice improves performance similarly, but the combination of physical/mental practice enhances performance significantly more than does mental practice alone.

Research in music practice also addresses the approaches musicians implement to facilitate the memorization of the pitch content of music (e.g., Chaffin & Imreh, 1997, 2001; Williamon et al., 2002). In these cases, musicians, particularly advanced players, organize practice around the formal structure of music to facilitate the cognitive encoding and recall of the music (Chaffin & Imreh, 1997). The topic of memorization is also addressed extensively by Rubin-Rabson. In one of her landmark studies, Rubin-Rabson (1940) tested the effects of multiple variables, including the spacing of practice, on pianists' memorization of music. Participants either practiced 10 trials of a new passage on a piano in one session or completed 5 trials of the passage in each of two sessions, separated by 1 hour or 24 hours. When retested, the performances of learners who spaced their practice across 1- and 24-hour rest intervals were superior to performances by those who completed a massed practice session. Rubin-Rabson's findings also show that distributing practice across time was most effective for "less-able" learners.

Since that time, the literature regarding massed versus distributed practice and their effects on skill learning has expanded. This growth has occurred in domains outside of music performance, however. Similarly, the current understanding of procedural learning is mostly based on experimental investigations of non-music skills. This aspect of learning deserves to be examined systematically in music learning contexts. Just as the study of skill learning in music contexts may contribute to current models of procedural learning, a clearer understanding of the types of motor learning that musicians frequently experience may further explain and perhaps even encourage a reevaluation of present-day pedagogical practices.

PURPOSE OF THE STUDY AND RESEARCH QUESTIONS

The purpose of the present study was to investigate the effects of brief rest intervals on within- and between-session motor sequence learning. In this research, I investigated the conditions that lead to changes in novices' performance of a simple keyboard sequence following 5-minute rest intervals. Further, I examined how skill repetition prior to the introduction of rest influenced performance outcomes. By way of behavioral evidence, I attempted to make inferences about the neurophysical bases for these behavioral effects.

This research addressed the following questions:

1. Is a 5-minute rest interval sufficient time for off-line learning (neurophysical processes that occur in the absence of practice) to induce behavioral changes in performance?

2. Does the introduction of a 5-minute rest interval either early in practice, before performance is stabilized, or later in practice, after block to block performance nears asymptote, differentially affect the development of behavioral changes during rest?

3. Does the offline learning that takes place across 5-minute rest intervals during practice affect the extent to which behavioral changes develop from subsequent, overnight memory consolidation?

Limitations of the Study

Non-musicians, persons naïve to finger-tapping skills common in piano performance, were chosen as participants in this study. Participants were undergraduate and graduate non-music majors at The University of Texas at Austin, who had had fewer than 3 years of formal instruction on a musical instrument and had participated in no substantial music making activities in the 5 years prior to this experiment. The definition of *non-musician* is specific to this study and may be inconsistent with definitions used in other research. Thus, generalizations of results to novices in other studies may be unjustified. Further, because this investigation focused on the skill performance of novices, generalizations to individuals with more extensive music experience are unwarranted.

In order to study solely the development of motor skill in music learning, sound feedback was eliminated for the entirety of this experiment. Participants performed the experimental task on a digital piano with volume levels turned off. It is inappropriate at this time to generalize findings to motor learning settings which use concurrent sound feedback (i.e., typical music performance contexts). Additionally, the 5-note sequence, which is identical to one used in several studies of sequential finger tapping (Hotermans et al., 2006; Kuriyama et al., 2004; Walker, Brakefield, Hobson et al., 2003; Walker, Brakefield, Seidman et al., 2003), is simpler than more complex tasks characteristic of many music skills. Generalizations of results obtained with this task to other skills, such as those that entail additional key presses, require bimanual coordination, or which are executed on a different apparatus or musical instrument, are unjustifiable.

Skill performance in this study was measured by the number of correct key presses per 30-second block (CKP/B). Though this measurement took into account *speed* and *accuracy*, two variables frequently used in the evaluation of motor and music performance, the unit of CKP/B is unique to this study and previous research by Duke and Davis (2006). Assessment of skill performance was based on definitions stated in this investigation and may not be directly comparable with definitions of skill performance in other research.

Chapter 2: Review of Literature

LEARNING AND MEMORY

Learning reflects permanent changes in behavior that result from repeated exposure to stimuli. Although the ability to recall new knowledge or execute a practiced skill is what most individuals recognize as learning, performance is only the outward manifestation of learning. A growing body of evidence accumulated over the past four decades demonstrates that humans and animals exhibit physical changes in the brain associated with the acquisition of new knowledge or skills. Recently, the study of behavioral changes in performance has been used to predict the nature of mechanisms in the brain that underlie learning (Karni & Bertini, 1997). Accordingly, more precise models of learning and memory at the neural level have led to a better understanding of how learning develops behaviorally.

Neuroplasticity, the hallmark of learning, is the ability of the brain to reorganize neural pathways in response to experiences, such as the performance of new skills. In fact, learning can be best described as long-lasting changes in the learner's brain that begin as a result of these experiences. Once new knowledge is acquired from rehearsal of a new skill, for example, the neural representation of that knowledge is gradually transformed into long-term memory, a process that may last hours and even days. Thus, changes that begin with initial exposure to a new stimulus continue long after learners have stopped consciously attending to the new experience.

Memory is the process by which learning is retained over time. Memory is classified as either declarative or procedural (non-declarative), depending on the nature of the behaviors with which the memories are associated and the neural pathways through which the memories are formed. *Declarative* memory, the conscious memory of facts and events, is usually acquired with only a limited number of exposures to the information being learned. Subcategories of declarative memory include *episodic* memory of events in one's past, such as the memory of a vacation taken as a child; and *semantic* memory, the memory of general knowledge not tied to a specific event, such as the recall of one's telephone number or of the lyrics of a song. Subject to forgetting, declarative memory can last indefinitely if recalled or rehearsed sufficiently. Declarative memory relies on the hippocampus and related medial temporal lobe structures for processing and storage (Gupta & Cohen, 2002).

Procedural memory, the memory for how to do things, is often characterized by learners' inability to explicitly verbalize the manner in which skills are executed. As compared to the acquisition of declarative memory, procedural learning often requires longer periods of acquisition and is usually achieved through repetition. Karni and colleagues (1995) describe procedural learning as the incremental gains in performance that develop over periods of practice and the passage of time. Two subcategories of procedural learning include motor and perceptual learning. *Motor* learning refers to the acquisition of skill in which movement and movement outcome are emphasized (Newell, 1991). *Perceptual* learning refers to the processing of sensory input. For example, visual and auditory tasks fall within the perceptual skill domain (Karni & Bertini, 1997). Unlike declarative memory, procedural memory does not appear to involve the hippocampus. Instead, the early acquisition of procedural skills recruits the cerebellum, frontal and parietal cortices, and basal ganglia. As skill learning continues, the supplementary motor area (SMA) and the motor cortices are also engaged (Doyon & Benali, 2005; Doyon, Penhune, & Ungerleider, 2003; Doyon et al., 2002; Karni, 1996; Karni et al., 1995; Penhune & Doyon, 2002, 2005; van Mier, Perlmutter, & Petersen, 2004; van Mier, Tempel, Perlmutter, Raichle, & Petersen, 1998).

Memory formation evolves quickly, with plasticity often beginning after a limited amount of exposure to a novel stimulus. Both declarative and procedural learning are shown to evolve over extended periods of time and progress through several distinct stages. Each phase of learning contributes to the formation, stabilization, or enhancement of new memory representations, and the entire process often continues for hours or days after the initial exposure to a stimulus has ended (Karni et al., 1998). The functional anatomies associated with the various stages of the learning process appear to be different, and the behavioral manifestations of underlying neural changes are also distinguishable from one stage to another.

This review of literature centers primarily on the current understanding of procedural skill learning. I discuss the neurophysical and behavioral aspects of procedural memory acquisition and retention from the earliest stages of practice through the later stages of learning, during which off-line memory consolidation processes serve to maintain and enhance skill performance.

LEARNING-RELATED NEUROPLASTICITY

The acquisition of new knowledge requires the activation of new pathways in the neural circuitry of the brain. These circuits are composed of neurons, or nerve cells, that receive and project information from and to other neurons. Nerve cells are equipped with a cell body, an axon, and dendrites. Electrical signals (i.e., nerve impulses) travel through a cell's axon until they reach the synapse, or junction, between two cells. Electrical signals then prompt the release of neurotransmitters through pre-synaptic nerve terminals, which in turn activate receptors in the post-synaptic targets that typically appear on dendrites, cell bodies, or other parts of nerve cells.

Synaptogenesis

The practice of skills induces neural activity. Improvements in skill performance represent changes in the amount and nature of neural activity used to encode and control skill movements. Progressively faster and more precise movements coincide with increased efficacy in synapses. In other words, as a result of physical repetition and increased learning, less and less energy is required to maintain neural firing. Additionally, learning results in *synaptogenesis*, or the formation of new synaptic connections within and between structures of the cortex (Kleim et al., 2004).

The creation of synaptic connections is driven by experience and learning; however, synaptogenesis also occurs during an organism's early developmental period, during which synapse formation is not necessarily tied to learning. During these early stages of development, the brain forms many more synapses than it will need during adulthood. Through a process of overproduction and pruning, synapses that are not called upon and recruited in the process of cognition and behavior disappear over time while stronger connections that are activated most frequently are preserved. What remains are the neural connections that are necessary for further sensory, motor, and cognitive development. Unlike synapse overproduction and loss, however, synapse addition persists throughout life, thus allowing learners to acquire and retain information throughout an entire lifetime.

Neural activity is fueled by oxygen that is conveyed through blood flow. Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) have been used to measure cerebral blood flow (CBF) for the purpose of determining where neural activity occurs at different stages in the learning process (Maquet et al., 2000; Peigneux et al., 2003). Neurosphysiological studies are consistent with behavioral data demonstrating that the acquisition and retention of new knowledge and skill is mediated by experience-driven and time-dependent modifications and reorganization of neural representations across multiple stages of learning.

Behavioral modifications in practice correspond to underlying neural activity driving changes in performance. Our current understanding of skill acquisition emphasizes the involvement of multiple stages of learning that correspond to changes in the underlying representation of procedural memory. While some brain structures show evidence of heightened neural activity during early practice of skills, other structures are recruited later, as practice progresses. Studies examining behavioral and neurophysiological aspects of skill learning indicate that some structures are implicated in the early execution of a task, whereas others take a more active role in preparing memory for long-term storage (Doyon & Benali, 2005; Doyon et al., 2002; Penhune & Doyon, 2005; Petersen, van Mier, Fiez, & Raichle, 1998; van Mier et al., 2004).

Functional Changes in the Brain during Learning

Recent studies show that the cerebellum is activated early in the practice of procedural skills (Doyon et al., 2002; Grafton et al., 1992; Penhune & Doyon, 2002). Evidence indicates that the cerebellum participates in the learning of movement sequences, with cerebellar activity highest during early practice when movements are usually slow and inaccurate. As performance becomes more precise, the cerebellum shows significant decreases in activity, suggesting that this structure may be involved in processes that facilitate error reduction (Penhune & Doyon, 2002; Petersen et al., 1998; van Mier et al., 2004).

Doyon and colleagues (2002) demonstrate that as activity decreases in the cerebellar cortex, the outer layer of the cerebellum, neural activity increases in the deep cerebellar nuclei, a group of nerve cell bodies inside the cerebellum. As performance becomes increasingly proficient, a transfer of plasticity in the neural representation of skills occurs between the cerebellar cortex and the deep cerebellar nuclei. As performance is gradually stabilized, the role of the deep cerebellar nuclei in turn declines, indicating that this structure may play a role in the establishment of motor movements needed to perform a skill fluently (Doyon et al., 2002; Penhune & Doyon, 2005).

Models of motor skill learning suggest that with extended practice beyond the stabilization of performance, skill learning becomes less dependent on the cerebellum. Once asymptotic levels of performance are reached, activity in the cerebellum decreases, and as practice progresses, the supplementary motor cortex (SMA), shows increasing neural activity (Doyon et al., 2002; Grafton et al., 1992; Petersen et al., 1998; van Mier et al., 2004). Whereas there is evidence that the SMA plays a role in sequence recognition, there is also support for its involvement in processing temporal components of skill performance (Petersen et al., 1998) and executing previously learned subsets of skills needed to perform the task at hand (Grafton et al., 1992). When comparing well-learned tasks to more recently-acquired tasks, research demonstrates that the SMA plays a role in the execution and retention of well-trained skills (Doyon et al., 2002).

Primary motor cortex (M1) is also shown to grow increasingly active during the repetition of new skills (Grafton et al., 1992; Karni, 1996; Karni et al., 1998; Penhune & Doyon, 2002; Petersen et al., 1998; van Mier et al., 2004). M1 demonstrates the greatest amount of change following the cessation of most neural activity in the cerebellar cortex and deep cerebellar nuclei (Penhune & Doyon, 2005) and recruitment of the SMA (Grafton et al., 1992). Also, M1 is found to grow increasingly more active during practice only after performance errors are minimized (van Mier et al., 2004).

Karni and colleagues (1995) provide evidence that M1 activates as early as the initial experience with new skills, but temporarily decreases in activity after a brief number of task repetitions, a characteristic of habituation (the suppression of response to a stimulus). M1 again becomes active during later practice. This reactivation suggests a switch from habituation to sensitization (the enhancement of response), which may be manifested behaviorally as performance improvements occurring during the later stages of practice. M1 activity continues to build progressively across days and weeks of practice, signifying the gradual development of an extensive representation of learned skills (Karni et al., 1995; Karni et al., 1998; Petersen et al., 1998). The gradual increase in activity following a switch from habituation to sensitization may contribute to processes that serve to retain newly-learned skills. Findings in the procedural learning literature implicate M1 in processes that will aid in the retention of procedural skill memory (Karni et al., 1995; Korman, Raz, Flash, & Karni, 2003; Muellbacher et al., 2002; van Mier et al., 2004).

Interestingly, Doyon et al. (2002) show large M1 activation during the performance of a learned motor sequence only after a 4-week delay between training and retest. Although these data do not coincide with other findings showing M1 recruitment early in learning, activation after long periods of delay lend support to the possibility that growth of activity in M1 is not repetition-dependent, but rather simply develops as a function of time (Floyer-Lea & Matthews, 2005; Penhune & Doyon, 2005). Whereas the majority of research examining functional changes in procedural skill representation centers around the structures discussed above, practice-related changes in activation have been observed in the thalamus, striatum, inferior parietal cortex, putamen, basal ganglia, and prefrontal cortex, among others. Recruitment of these structures occurs either within or across practice sessions and plays a role in both the automatization and retention of newly learned skills (Muller, Kleinhaus, Pierce, Kemmotsu, & Courchesne, 2002; Penhune & Doyon, 2002, 2005; Petersen et al., 1998; van Mier et al., 2004).

ACTIVE PRACTICE INITIATES SKILL ACQUISITION

Physical repetition of novel skills sets in motion the process of procedural learning. During practice, the learning of new skills is measurable by the level of performance attained within a given session, which may last anywhere from minutes to hours. When learners initially perform novel skills, the first few repetitions are often slow, inaccurate, and uncoordinated. In many cases, large, rapid gains in performance occur within a relatively small number of repetitions. This initial stage of skill practice—the *fast* period of learning—is characterized by large, incremental gains in performance as learners adapt to new motor and perceptual demands (Atienza, Cantero, & Dominguez-Marin, 2002; Costa, Cohen, & Nicolelis, 2004; Karni et al., 1998; Korman et al., 2003; Maquet, Peigneux et al., 2003). Skill improvements during this time include increases in speed or reaction times, decreases in errors, and/or improvements in synchronizing movements to produce more fluid execution.

After the initial stage of acquisition, the rate of skill improvement begins to slow down. The gradual deceleration in the rate of performance gains characterizes a second period, appropriately termed *slow* learning. This subsequent period of skill acquisition is thought to begin during practice and continue even after practice is terminated. It is important to note that the label "slow learning" has consistently been used to identify behavioral and functional changes in the cortex that occur *following* the end of practice (Costa et al., 2004; Karni et al., 1998; Korman et al., 2003; Maquet, Laureys et al., 2003; Mednick et al., 2002). However, Hauptmann and colleagues (2005) suggest that slow learning mechanisms may, in fact, commence within a practice session, and more specifically, as soon as the rate of large performance improvements begins to decrease.

Slow learning is occasionally referred to as *overlearning*, behaviorally characterized by practice beyond the saturation of performance gains, during which skill execution is consistently fluent (Petersen et al., 1998; Puttemans, Wenderoth, & Swinnen, 2005). Large, incremental changes in skill are seldom observable during this time. For this reason, learners rarely continue practicing skills for very much longer once overlearning is reached. During this time, however, extensive amounts of learning-dependent neural plasticity temporarily dissociated from performance changes may be taking place covertly (Kleim et al., 2004). Although practice during overlearning does little to induce additional skill gains, reaching this phase of acquisition may serve to ensure that neural processes associated with new learning will continue once practice is terminated.

In effect, the cessation of practice does not suggest that the capacity for learning has ended. Instead, learning beyond this point develops in the absence of practice, and its behavioral outcomes are observable when skills are recalled at a later time (Walker, 2005; Walker, Brakefield, Hobson et al., 2003; Walker, Brakefield, Seidman et al., 2003).

Skill Learning Follows Active Practice

Wake-Based Stabilization of Memory

Behavioral and neural modifications that occur during the acquisition of new skills are thought to be labile and susceptible to interference. New memory representations, formed during practice, must undergo further transformation before becoming more permanent (Walker, 2005). The process of physical change that occurs following active learning experiences is termed *memory consolidation* and involves not only a reorganization of the neural circuitry that comprises new memories, but also a relocation of memory representations in the cortex (Muellbacher et al., 2002; Walker, 2005).

Through the process of consolidation-based *stabilization*, which begins during initial skill repetition and continues for up to six hours following practice, new memories become increasingly resistant to interference from competing stimuli. A memory's resistance to interference is the end product of successful consolidation-based stabilization, and behavioral outcomes are characterized by the maintenance of performance levels observed at the end of training (Brashers-Krug et al., 1996; Shadmehr & Brashers-Krug, 1997; Stickgold, Whidbee, Schirmer, Patel, & Hobson, 2000; Walker, Brakefield, Seidman et al., 2003).

The progression of consolidation processes exclusively over hours of wake is typically thought to facilitate the maintenance of skills. Consequently, performance seems unchanged from that observed at the end of skill practice. Whereas behavior appears unaffected, functional imaging of the brain demonstrates that within 4 to 6 hrs following acquisition, the brain engages new regions to encode the task. Specifically, there is a shift from prefrontal regions of the cortex to the premotor, posterior parietal, and cerebellar cortex structures, suggesting that with the passage of time, there is a change in the neural representation of a new memory, resulting in its more permanent state (Shadmehr & Holcomb, 1997).

Consolidation-based stabilization has been demonstrated repeatedly through various experimental methods in human and animal subjects. Muellbacher and colleagues (2002) show that repetitive transcranial magnetic stimulation (rTMS) of the primary motor cortex (M1) in humans immediately after skill practice interferes with the maintenance of new procedural skill memory. If applied after a 6-hour, post-training interval, no interference effects are observed. The cortical injection of protein synthesis inhibitors (Bourtchouladze et al., 1998) and administration of electroconvulsive shock (Trepel & Racine, 1999) to rats after a learning period are shown similarly to interrupt the consolidation process and prevent the retention of newly-acquired skills. When these procedures are introduced within six hours of skill acquisition, memory is degraded; when the same procedures are introduced later, after wake-based consolidation has been completed, no decrements in memory are observed.

Sleep-Based Enhancement of Memory

Whereas wake-based consolidation serves mainly to stabilize memory representations and preserve behavioral performance over time, this phase of consolidation generally does not result in further "off-line" learning. New skill memories undergo further processing during periods of post-training sleep, during which memories become more resistant to interference and are in some respects are enhanced, as evidenced by the fact that when skills are recalled at a later time, absent further practice, performances are nevertheless improved. This phenomenon has been observed in both simple and complex motor skills (Duke & Davis, 2006; Hotermans et al., 2006; Kuriyama et al., 2004; Maquet, Schwartz, Passingham, & Frith, 2003; Simmons & Duke, 2006; Walker, Brakefield, Hobson et al., 2003; Walker, Brakefield, Seidman et al., 2003), auditory discrimination skills (Atienza & Cantero, 2001; Atienza et al., 2002; Atienza, Cantero, & Stickgold, 2004; Gaab et al., 2004), visual discrimination skills (Karni, Tanne, Rubenstien, & Askenasy, 1994; Mednick, Nakayama, & Stickgold, 2003; Mednick et al., 2002; Stickgold, James, & Hobson, 2000; Stickgold, Whidbee et al., 2000), verbal skills (Fenn, Nusbaum, & Margoliash, 2003), and enumeration learning (Hauptmann & Karni, 2002; Hauptmann, Reinhart, Brandt, & Karni, 2005).

Evidence that consolidation-based *enhancement* occurs primarily over periods of sleep and not over equal intervals of time awake is shown by Walker and colleagues (2002). Following a training session on a sequential finger-tapping task, learners were retested after a 12-hour period that did or did not include sleep. Significant improvements in the speed and accuracy of the test sequence were observed only after intervals that included sleep. Similar findings are demonstrated in music learning contexts as well. Simmons and Duke (2006) show that learners performed with significantly fewer errors when they recalled a keyboard sequence following a 12-hour interval that included sleep than were observed when sequences were recalled after a 12-hour interval without sleep. Results suggest that sleep states provide optimal conditions, not available during time awake, that allow for more than the mere prevention of interference. New skill memory representations undergo further processing during sleep, optimizing future performance.

The current understanding of memory consolidation suggests that the chemical processes that occur during sleep trigger neural modifications that enhance new skill memories (Benington & Frank, 2003). In turn, the modifications in neural activity are accompanied by shifts in functional anatomy (Walker, 2005). Early in the night, regions including the thalamic nuclei, basal ganglia, prefrontal cortices, and medial temporal lobe show decreases in activity as compared to wake (Maquet et al., 1996). Later in the night, areas that show an increase in activation relative to wake are the thalamic nuclei, prefrontal lobes, amygdala, hippocampus, and anterior cingulate cortex. During this time, the posterior cingulate and parietal cortex contrastingly show decreases in activity as compared to wake (Maquet et al., 1996). The end result of neural reorganization during sleep is a more permanent state of new memory, which is reflected behaviorally in faster and more accurate performances when skills are recalled.

Post-training enhancements in skill learning are often related to specific stages of sleep, which are classified as either non-rapid eye movement (NREM) or rapid eye movement (REM) sleep. Each stage differs in terms of depth of sleep, eye movements, dream frequency and intensity, muscle tone, and neural activation (Stickgold, 1998). NREM sleep includes four levels (stages 1 to 4); stages 3 and 4, the deepest levels of sleep, are known as slow-wave sleep (SWS). NREM is characterized by activations of large, slow-wave electroencephalographic (EEG) fluctuations and sleep spindles (short, synchronized EEG oscillations). During this stage, sensation and perception are dull or absent. Rapid eye movement (REM) sleep, in contrast, is characterized by vivid hallucinations and dreams, and heightened and internally-generated sensation and perception. The occurrence of low-voltage, fast-wave activity during this period is similar to wake, though muscle tone is decreased significantly (Chase & Morales, 1990; Hobson, 2005). REM and NREM sleep alternate across the night in 90-minute cycles, with NREM sleep dominating in the first half of the night and REM predominating in the latter half of the night.

Distinct sleep stages are often implicated in the consolidation-based enhancement of motor and perceptual skills. For instance, post-sleep enhancements of motor skill performance are linked to increases in the strength of EEG slow waves during SWS (McClelland, McNaughton, & O'Reilly, 1995). Skill improvements, specifically those in motor adaptation tasks, serial reaction time tasks, motor sequence skills, and pursuit rotor tasks, are proportionally linked to time spent in NREM sleep (including stage 2 and SWS periods) (Huber, Ghilardi, Massimini, & Tononi, 2004; Smith & MacNeill, 1994). Further evidence for a relationship between procedural skill enhancements and the amount of stage 2 NREM sleep includes data indicating increased sleep spindles after training (Briere, Forest, Lussier, & Godbout, 2000).

REM sleep is also found to play a role in off-line motor skill learning (Fischer, Hallschmid, Elsner, & Born, 2002; Plihal & Born, 1997). Fischer and colleagues (2002) demonstrate enhancements in motor sequence performance that are correlated to the amount of time spent in post-training REM sleep. Additionally, functional neuroimaging of the brain using Positron Emission Tomography (PET) during sleep, and in particular during periods of REM, reveal that several brain areas activated during motor skill practice are significantly more active during REM in learners who train on a task than they are in untrained subjects (Maquet et al., 2000). Findings such as these imply that reactivated brain regions associated with skill learning, and more importantly the connectivity of reactivated brain regions to one another, during post-training REM sleep indicate the reorganization of new memory representations, a hallmark of consolidation (Laureys et al., 2001).

The necessity of REM sleep is demonstrated in the off-line development of perceptual skill enhancements as well. The period of time spent in REM is directly related to the magnitude of improvements in language learning following sleep, for example (De Koninck, Christ, Proulx, & Coulombe, 1989). In fact, De Koninck and colleagues report that the amount of learning *prior* to sleep influences the duration of subsequent REM stages. Karni and colleagues (1994) show that visual texture discrimination performance is unimproved after the selective deprivation of REM sleep. Additionally, visual discrimination skill enhancements are also shown to be correlated with the amount of time spent in SWS in the first quarter of the night (SWS1) and the amount of REM in the last quarter (REM4), with an even stronger correlation existing between behavioral improvements and the product of time spent in SWS1 and REM4 (Stickgold, Whidbee et al., 2000). These data support a so-called sequential hypothesis, which proposes that both NREM and REM periods may be necessary for successful memory consolidation of procedural skills (Gais, Plihal, Wagner, & Born, 2000; Giuditta et al., 1995; Stickgold, Whidbee et al., 2000).

Different skill types may be uniquely affected by distinct sleep stages or combination of sleep stages. However, a general assertion across procedural learning domains is that the robustness of skill learning depends heavily on the first night of sleep following practice. Depriving learners of sleep after the training of new skills is shown to cause significant deficits in memory consolidation. The reduction in learning is not caused by fatigue, because the effect persists even after learners recover from sleep deprivation (Maquet, Schwartz et al., 2003; Stickgold, James et al., 2000). Impairments in learning may also result from selective deprivation of specific sleep stages, such as SWS early in the night and REM sleep in the last quarter of the night (Beaulieu & Godbout, 2000; Smith, 1995, 1996).

There is speculation that skill learning is predominantly driven by the initial practice session and subsequent nights of sleep. This may be plausible given that considerably less learning develops across succeeding practice periods than occurs during the initial training session. Multiple nights of sleep, on the other hand, may continue to produce overnight enhancements, though each succeeding night to a lesser degree than the night before (Duke & Davis, 2006; Walker, Brakefield, Hobson et al., 2003) While the stabilization phase of consolidation is shown to consistently evolve in a time-dependent manner and within a limited number of hours following practice, the development of skill enhancements may be primarily dependent on the availability of sleep across successive nights (Stickgold, 2005). Thus, slow learning, which begins during active practice and continues across post-training wakefulness and sleep, may progress across days, weeks, and even months (Hauptmann & Karni, 2002; Korman et al., 2003; Ofen-Noy, Dudai, & Karni, 2003).

Complete cycles of sleep stages occur most often during extended periods of sleep, but overnight sleep is not the only time during which consolidation-based enhancements may develop. Daytime naps have been shown to result in performance enhancements of procedural skills, provided that the naps include intervals of REM sleep (Mednick et al., 2003; Mednick et al., 2002).

Interference of Memory Consolidation Processes

After practice, fragile memories become stabilized and resistant to interference over time. The process of consolidation, however, may be disrupted by such factors as trauma to brain structures, by any number of chemical or electrical agents, or by behavioral interference. Often, learning a second procedural task within four to five hours following the acquisition of a similar task, for instance, is shown to retroactively interfere with stabilization of memory, resulting in the "unlearning" of the skill learned first (Brashers-Krug et al., 1996; Shadmehr & Brashers-Krug, 1997). Learning a second skill in close temporal proximity may also inhibit further improvements in performance of the first skill, even after overnight sleep (Walker, Brakefield, Hobson et al., 2003). In some instances, however, the learning of two successive tasks is shown to elicit a generalized practice effect that does not interfere with, but rather enhances, the memory of a skill learned first. In such cases, motor sequences, practiced in close temporal proximity, show enhancements the following day, though the effect is greater for the sequence learned second (Duke & Davis, 2006).

Reconsolidation of Recalled Memory

Walker et al. (2003a) show that the simple recall of a previously consolidated skill may return the memory trace to a labile state, thus making it susceptible to interference and requiring a period of reconsolidation. When a second sequence is learned after the brief recall of an already-consolidated sequence, the first learned sequence shows a marked decrease in performance following a second night of sleep, returning performance level to that observed at the end of training (Walker, Brakefield, Hobson et al., 2003). Yet, findings using similar finger-tapping skills to those used by Walker et al. (2003a) indicate that learning a new sequence following the recall of an already-consolidated sequence does not yield such detrimental effects, but rather merely interferes with further sleep-based enhancements of the sequence learned first (Duke & Davis, 2006). To date, Walker and colleagues, and Duke and Davis are the only authors to examine the behavioral effects of reconsolidation in human motor learning. Inconsistencies in the results of their studies are not surprising given conflicting evidence regarding the reconsolidation of procedural memory in rats (Milekic & Alberini, 2002; Taubenfeld, Milekic, Monti, & Alberini, 2001). Further, some researchers propose that reconsolidation only occurs in recently acquired memories. Dudai and Eisenberg (2004) and Milekic and Alberini (2002) demonstrate that the vulnerability of memory to interference decreases as the amount of time between training and recall of the task increases.

Skill Practice Influences Memory Consolidation

Skill repetition induces learning-related neural activity. Physical practice also influences the rate at which consolidation progresses after practice ceases. Generally, saturating performance gains within a practice session is thought to be necessary to ensure that neural modifications associated with consolidation will continue once practice ends (Hauptmann et al., 2005; Korman et al., 2003). Of course, the absolute number of repetitions needed to stabilize performance for any given skill varies among individuals and among tasks. Yet, most learners who reach asymptotic levels of performance at training show improvements in skill performance following a night of sleep (Hauptmann et al., 2005). Additionally, once performance is fluid, repetition beyond the saturation point offers no significant benefits in increasing the magnitude of sleep-based performance improvements (Walker, Brakefield, Seidman et al., 2003). Walker and colleagues (2003) demonstrate that learners who practice a simple motor sequence for 24 30-second blocks achieve a slightly superior performance level than learners who practice for 12 blocks. However, learners in both groups show similar rates of enhancement in speed and accuracy across a night of sleep.

However, other evidence suggests that limited practice, or practice that is halted within early stages of repetition, during which large gains in performance are still being made, is adequate to ensure that consolidation will progress following practice. In these instances, the enhancement effects of sleep-based consolidation may appear only after extended time intervals, however (e.g., 48 hours versus 24 hours) (Hauptmann & Karni, 2002). These findings indicate that even a small amount of practice is enough to effect some level of change in underlying structures devoted to skill learning and long-term memory storage. Additionally, the slow stage of learning, characterized by modest improvements in performance within and across practice sessions, may evolve primarily as a function of time, further distinguishing itself from the more repetition-dependent fast stage of learning.

ADDITIONAL FINDINGS

The majority of extant research regarding the effects of consolidation-based enhancement procedures utilizes simple motor skills. Recent studies, however, suggest that more complex skills may also benefit from sleep. For example, Simmons and Duke (2006) report that musicians who learned a 12-note piano melody performed significantly more accurately after a night of sleep than after equally long periods of wake. Similarly, complex finger-tapping tasks that require additional key presses and bimanual coordination show greater improvements following overnight sleep than do simpler motor sequences (Kuriyama et al., 2004). In their study, Kuriyama and colleagues also demonstrate that not all transitions (i.e., movements between two consecutive finger taps) of the finger-tapping task improved at the same rate; transitions that appeared most difficult (i.e., slowest) at the end of training showed significantly greater enhancements after sleep than did transitions that were performed most rapidly at the end of practice. Their findings suggest that sleep-dependent consolidation may provide the most benefit to skill components that are most difficult to initially perform.

Though evidence thus far is impressive, it is premature to assume that all motor skills benefit from sleep or that skills may not be capable of enhancements during wake. For example, two large categories of skill learning—kinematic and dynamic adaptation tasks, requiring a learner's continuous adjustment to changes in the learning environment—have yet to show sleep-dependent learning (Brashers-Krug et al., 1996). Evidence also reveals that off-line improvements may evolve across wake hours, suggesting that time alone may support the consolidation-based enhancement processes for some skill learning. For example, studies in auditory learning show that participants demonstrate performance improvements that develop over both wake and sleep (Atienza & Cantero, 2001; Roth et al., 2005). In a music context, improvements on a 12-note keyboard sequence have been demonstrated across intervals without sleep, as well (Simmons & Duke, 2006).

Learners' awareness of what is being learned during the acquisition of new skills also influences the time course of consolidation-based enhancement processes (Born & Wagner, 2004). In serial reaction-time (SRT) tasks, learners who are made explicitly aware of a repeating pattern in a sequence of key presses show improvements in speed following a night of sleep. Learners unaware of the sequence, and who thus learn the same sequence implicitly, show improvements across both wake and sleep (Robertson, et al., 2004). Robertson and colleagues propose that implicit learning is time dependent, whereas the development of explicit skills relies more so on the availability of sleep.

In some cases, explicit skill learning may also develop over wake hours following practice, but only if consolidation of the explicit component of the task is disrupted. Brown and Robertson (2007) show that learners made aware of an embedded pattern during the training of an SRT task show improvements in skill performance after 12 hours awake, but only when a declarative task (e.g. learning a word list) is introduced immediately following sequence training. The declarative interference task disrupts the consolidation of the explicit component of the task, demonstrated by learners' inability to verbalize the previously learned pattern when retested, but induces consolidation-based enhancements of the motor skill. Brown and Robertson suggest that off-line improvements in motor learning that develop across wake depend on the disengagement of the interaction between declarative and procedural memory systems.

In some cases, skill improvements are observed after periods of rest comprising *minutes*. Recently, Hotermans and colleagues (2006) showed that learners' performance of a simple motor sequence improves significantly after 5- and 30-minute rest intervals. They suggest that this boost is indicative of *reminiscence*, an enhancement in performance typically observed after periods of rest.

The term reminiscence was coined by Ballard (1913) in an effort to label improvements in performance that developed while learners rested from practice. A number of experimental studies were conducted from the 1940s through the 1970s to examine the effects of rest periods composed of minutes (Ammons, 1947; Denny, 1951; Eysenck & Frith, 1977; Holland, 1963). Using a series of pursuit-motor tasks, which usually involves participants moving a cursor to a moving target, the authors reliably demonstrate that performance improves significantly following rest periods of 5 to 15 minutes. Improvements were found to be temporary, however, with performance returning to that of pre-rest levels within a limited number of repetitions (Ammons, 1947; Denny, 1951; Eysenck & Frith, 1977; Holland, 1963). The effects of extended rest periods were not formally addressed again until Heuer and Klein (2003) demonstrated that introducing a 3-minute rest interval during practice significantly improved performance of a serial reaction time (SRT) task. In their study, the rest interval was introduced later in practice, immediately prior to the last block of training.

PILOT STUDY

In efforts to examine how improvements in motor sequence performance develop from limited amounts of practice and across periods of rest, I designed a pilot experiment that served as the impetus for the present study. Nonmusicians (N = 29) trained on a 5-note keyboard sequence (identical to the test sequence used in the present study) with their left (non-dominant) hand over three 30-second blocks, alternating with 30-second pauses. To examine the extent to which performance improves over various rest intervals, learners were retested following 30 seconds (N = 10), 5 minutes (N = 9), or 24 hours (N = 10). At retest, participants practiced the sequence over three 30-second blocks alternating with 30-second pauses.

Results from the experiment show that performance of the sequence improved between the beginning of training and end of retest for all learners, and participants demonstrated significant enhancements in performance following rest intervals of 5 minutes, $t(8) = 7.09$, $p < .0001$, and 24 hours, $t(9) = 6.08$, $p < .0002$. In fact, learning of the simple keyboard sequence improved at a greater rate across a 5-minute rest interval (50.9%) than over a night of sleep (39.0%) (see Figure 1).

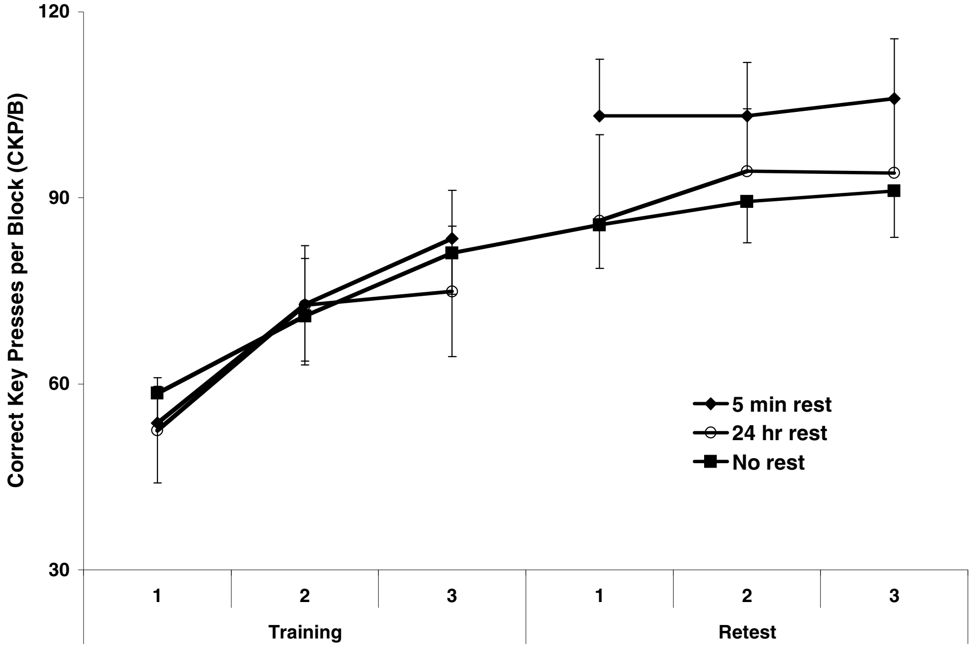

Figure 1. Performance of a brief keyboard sequence across training and retest sessions. Learners rested for 30 seconds, 5 minutes, or 24 hours between sessions.

These data indicate that three blocks of practice is sufficient to trigger significant sleep-based enhancements for this particular task. However, individual block data reveals that retest performance following a night of sleep is comparable to projected retest improvements based on continued practice alone. Therefore, the degree of enhancement provided by sleep-based consolidation may be dependent on the amount of practice during training. That is, additional repetition of the sequence may have yielded greater skill improvements following a 24-hour rest interval, as shown in a previous study in which 12 blocks of training on an identical task was sufficient to trigger robust enhancements following sleep. Post-sleep enhancements, in that experiment, surpassed projected retest improvements based on continued practice alone (Duke & Davis, 2006).

Unlike retest performances after a 24-hour rest interval, learners' performances following a rest period of 5 minutes surpassed projected improvements based solely on continued repetition. These results indicate that a limited amount of practice, though insufficient to yield the full benefits of sleep-based consolidation, induces enough neural activity for the development of significant off-line effects on performance over 5 minutes or rest.

The bases for these off-line improvements following such short time periods remain unknown. However, some researchers propose that reminiscence may represent the dissipation of physical or mental fatigue over rest intervals (Heuer & Klein, 2003). Unlike the training sessions of older studies, however, which typically introduced an extended rest interval after massed practice (i.e., repetition without the opportunity for rest), more recent studies, including the pilot experiment discussed above, afforded learners with brief pauses between sets of repetitions (Davis, 2006; Heuer & Klein, 2003; Hotermans et al., 2006). As muscular fatigue is certainly a possibility after periods of massed practice, intermittent pauses between sets of repetition were used to diminish the possibility of such fatigue (Duke & Davis, 2006; Hotermans et al., 2006; Walker, Brakefield, Hobson et al., 2003). A dissipation of physical or mental fatigue, therefore, may be an unlikely explanation for the enhancements in performance following rest periods of 5 minutes (Davis, 2006; Hotermans et al., 2006), though the possibility cannot be ruled out based on current findings.

Reminiscence effects may be attributable to the elimination of inhibition accrued during practice (Ammons, 1947; Kimble, 1952). The repetition of skills initially activates neural networks that subsequently drive changes in performances. Following extended periods of practice without the availability of rest, a saturation of neural activity induces inhibitory responses (i.e. suppression of activity) that interfere with the potential for further skill improvement. Like the effects of physical fatigue, inhibitory effects quickly intensify over periods of continuous repetition, with practice intervals of increasing duration producing the greatest inhibition. Ammons (1960) reports that shorter periods of practice alternated with brief intervals of rest allow for inhibitory effects to be eliminated more frequently. But, regardless of the opportunity for rest, inhibition nevertheless amasses as a function of practice (Kimble, 1952). Brief periods of rest may certainly offer more than mere relief from mental and physical fatigue during skill repetition. Nevertheless, the theory of practice-induced inhibition also prompts questions regarding the processes in action during the accrual and loss of inhibitory effects and the relationship of these to memory consolidation.

It is certainly possible that memory consolidation processes, previously believed to develop fully over hours following the end of practice, may be triggered by a limited amount of repetition and evolve across any available rest periods within practice sessions. However, to date, there is no existing neurological evidence to suggest that performance changes following brief periods of rest are a product of memory consolidation processes, per se. The nature of neural processes occurring immediately following the termination of practice may differ from consolidation processes that develop over longer periods of time and in turn, may produce effects that are only temporarily reflective of performance changes that will occur after longer periods of rest.

The effects of brief rest periods on skill acquisition are discussed to a limited degree in the literature regarding massed and distributed practice. Distributed practice (i.e., practice spaced across time with intermittent rest intervals lasting minutes, hours, or days) is found to enhance learning more so than massed practice (Dail & Christina, 2004; Lee & Genovese, 1988; Rubin-Rabson, 1940; Shea, Lai, Black, & Park, 2000). Distributed practice in experimental contexts is most often spaced across intervals longer than several minutes, and the beneficial effects are more often than not observed in the learning of tasks of low physical and mental complexity. Still, findings related to distributed practice provide impetus for the study of the effects of short periods of rest on motor skill learning. Several researchers propose that the superiority of distributed practice can be attributed to the biological processes that develop over rest and subsequently enhance performance (Dail & Christina, 2004; Shea et al., 2000). The opportunity for rest between practice sessions, regardless of the duration, may allow consolidation processes to proceed and thus enhance the skill learning processes.

SUMMARY AND CONCLUSIONS

Non-invasive brain imaging and neurophysiological interventions offer support to behavioral studies demonstrating the modifications in skill learning that occur not only as a result of physical experience with new stimuli, but also in the absence of practice. The multiple stages of skill learning appear distinct and independent of one another in terms of the behavioral indicators with which they are associated and the neural functions through which each stage progresses. The stages of memory acquisition, stabilization, and enhancement are closely related, however. Closer examination of the conditions under which practice and off-line processes interact may provide more insight into the mechanisms of skill learning. The nature of motor skill acquisition warrants further investigation, including a systematic study of music skills, which introduce additional variables that may very well influence motor acquisition and retention.

Skill learning is reliably shown to develop through active practice and by way of the processes of memory consolidation. To date, the effects of memory consolidation, which evolve over the hours following skill practice, have been studied using a variety of procedural tasks and training protocols. Yet, there is paucity in the literature regarding the off-line processes that develop immediately after skill practice. The present study was designed to examine the development of skill learning over brief periods of rest, a phenomenon first investigated in the 1940s, but given little attention in more recent years. Through this study, I examined whether the presence, and more specifically, the temporal placement of 5-minute rest intervals affects learning of a brief keyboard sequence. Also, I sought to determine the relationship between within-session learning following 5-minute rest intervals and post-training memory consolidation processes. The overarching goals in this study were to contribute to the current understanding of motor skill learning and to provide impetus for further systematic examination of motor acquisition and retention in music performance contexts.

Chapter 3: Method

Two experiments were created with the aim of examining behavioral changes in the performance of a simple keyboard sequence following 5-minute rest intervals. Each experiment functioned not only to identify the behavioral outcomes of brief periods of rest, but also to help clarify the bases of these effects. Both experiments were approved by the Institutional Review Board at The University of Texas at Austin.

Participants

Non-musicians, persons naïve to finger-tapping skills common to piano performance, were chosen as the primary sample for this study. This group was selected to facilitate the examination of the effects of rest on the skill performance of novices. Prospective participants were undergraduate and graduate students at The University of Texas at Austin. Students were solicited in person or via email. At the time of initial contact, I described the study as one intended to examine motor learning in a music context, and I informed students of the availability of monetary compensation for their participation. Students who expressed interest in participating in the study voluntarily completed a survey in which they reported their participation in formal music instruction (e.g., violin lessons) and/or in ensemble performance (e.g., high-school marching band, church choir). Students also indicated the years during which participation had taken place (e.g., 1998-2000) (see Appendix A).

I selected participants for the study on the basis of their current or previous music making activities. Students who had had fewer than 3 years of formal instruction on a musical instrument and had participated in no music making activities in the 5 years preceding the experiment were contacted via email. The email described the time commitment involved in the study and the need to abstain from caffeine, alcohol, and mind-altering substances 12 hours prior to and during participation in the study.

62 right-handed individuals took part in either Experiment 1 or Experiment 2. Conditions within each experiment were assigned randomly to participants at the time of training. All individuals received monetary compensation in the amount of $10.00 at the completion of their participation.

SETTING

Participants were tested individually in a small room free of distractions located at The University of Texas at Austin School of Music. I proctored all experimental trials and was the only other person present in the room during testing.

Participants performed the test sequence on a Roland KR-4700 Digital Piano with full-sized and fully-weighted keys. Volume levels on the digital piano were turned off for the duration of the procedure. Auditory feedback was eliminated in order to study solely the development of motor memory in a sequential key press task. To reduce distraction from extraneous sounds, participants wore Bose QuietComfort 2 acoustic noise-canceling headphones (Model QC 2).

The digital piano was connected to a 12-inch Mac PowerBook (model number A1010) by way of a Midiman USB Midisport 2x2 MIDI Interface. Musical Instrument

Digital Interface (MIDI) data were recorded using Max/MSP Runtime, version 4.5.2 (Puckette & Zicarelli, 2004) installed on the computer. The Max/MSP software program was identical to the software used for previous investigations using similar protocols (Davis, 2006; Duke & Davis, 2006). The program was set up to display the test sequence and record performance data. Throughout the entire procedure, participants watched the computer screen, which was mounted at the level of the keyboard's music rack.

TASK

Participants learned a finger-tapping sequence with their left (non-dominant) hand using the keys F3, G3, A3 and B3 on the digital piano. The sequence was 2-5-3-4-2, with numbers indicative of traditional piano finger numbers (i.e., 2 represents index finger, 3 represents middle finger, etc.). This task is identical to one used in similar protocols in which subjects practiced a finger-tapping sequence on a piano keyboard (Davis, 2006; Duke & Davis, 2006) or a computer keyboard (Hotermans et al., 2006; Kuriyama et al., 2004; Walker, Brakefield, Hobson et al., 2003; Walker, Brakefield, Seidman et al., 2003).

At the start of each session, I read the following instructions to each participant:

> Tonight you will learn a simple, left-handed sequence on the piano and will practice the sequence for the next few minutes. Please place your left-hand thumb on the key with the sticker (indicated C4, middle C on the piano). Rest the remaining fingers of the left hand on the white keys below your thumb (I assisted participants in placing their second through fifth fingers on B3, A3, G3 and F3). This is the sequence you will be learning.

On the computer screen were the finger numbers of the test sequence (2-5-3-4-2). Below each finger number was a circle that illuminated each time a key was pressed. The circles illuminated in order from left to right, regardless of whether subjects pressed a correct key. Thus, the illuminated circles did not provide accuracy feedback, but were intended only to help subjects maintain their place in the sequence (see Figure 2).

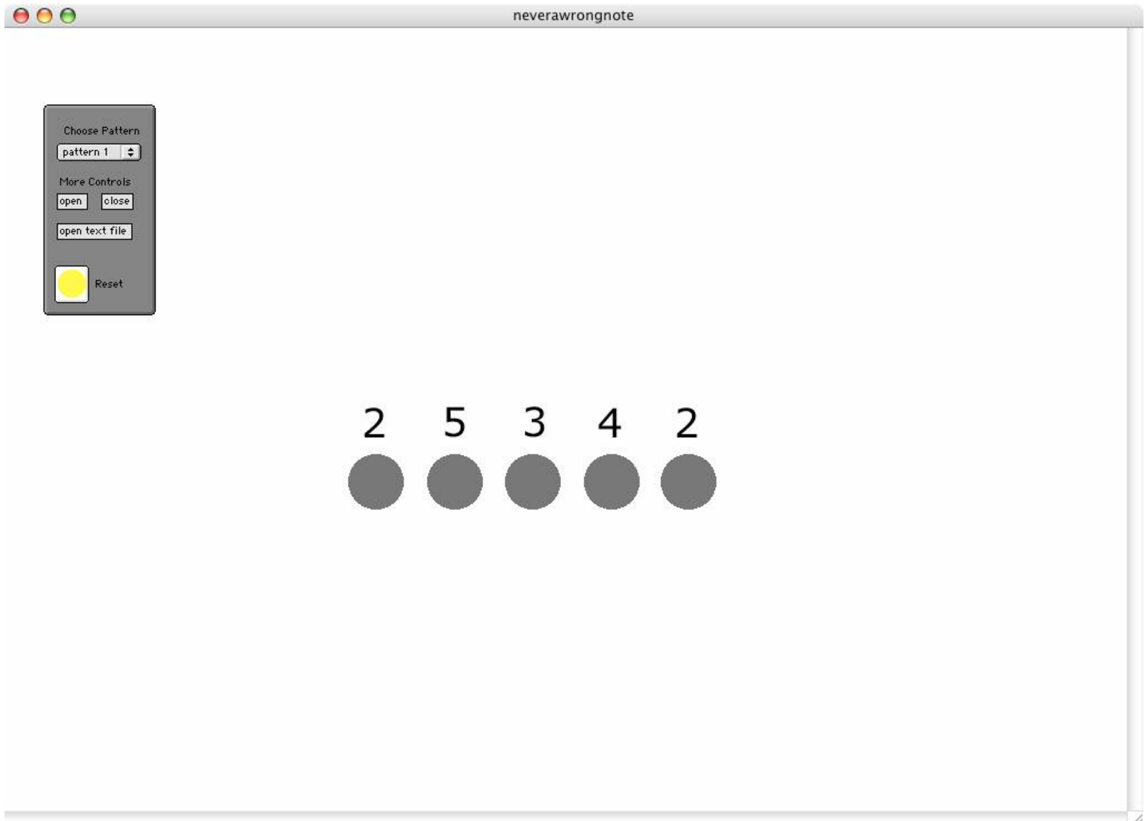

Figure 2. Screen observed by participants during the experiment.

Participants were instructed to play through the test sequence once slowly to ensure the use of correct fingerings and correct notes. If participants struggled in this initial trial, they were instructed to play the sequence slowly again until the use of correct fingerings was demonstrated. I continued with the following instructions:

> You noticed that circles illuminated each time you pressed a key. The circles are there to help you keep track of where you are in the sequence.

> Keep in mind that the circles will illuminate regardless of whether you use the correct fingering. If you make a mistake, do not correct your mistake. Continue with the next key press until you reach the end of the sequence.
>
> When I tell you to start, you will repeat the sequence as quickly and accurately as possible until I stop you. In other words, play the sequence as many times as you can and as accurately as you can until I tell you to stop.

Participants were given the opportunity to ask questions before they began their performances. Participants' first key press initiated the computer's data recording.

In order to limit physical and mental fatigue that may result from repetitive finger motions over extended durations, each practice block comprised a 30-second interval of physical practice and was followed by a 30-second pause. At the completion of 30 seconds of practice, data collection stopped and circles ceased to illuminate. At this time, I instructed participants to stop repeating the sequence.

PROCEDURE

The setting and task are identical for both of the experiments described below. The main distinction between Experiment 1 and Experiment 2 is the length of practice afforded to participants and the presence and temporal position of a 5-minute rest interval.

Experiment 1

This experiment was designed for the purpose of studying the extent to which within-session performance of a novel keyboard sequence is influenced by a 5-minute rest interval. Data from this experiment were also used to determine whether behavioral changes after a 5-minute rest interval could predict performance enhancements following overnight memory consolidation processes.

Training

26 participants, randomly assigned one of two experimental conditions, were trained in the evening between the hours of 8:00 and 10:30 PM. At training, participants practiced the test sequence, 2-5-3-4-2, with their left (non-dominant) hand for 6 blocks. Recall that each practice block consisted of participants' repetition of the sequence "as quickly and accurately as possible" for 30 seconds followed by a 30-second pause. In the Rest group ($N = 13$), a 5-minute rest interval was inserted in place of the 30-second pause between Blocks 3 and 4 (midway through session). The No-Rest group ($N = 13$) completed 6 blocks of practice without an extended rest interval (see Figure 3).

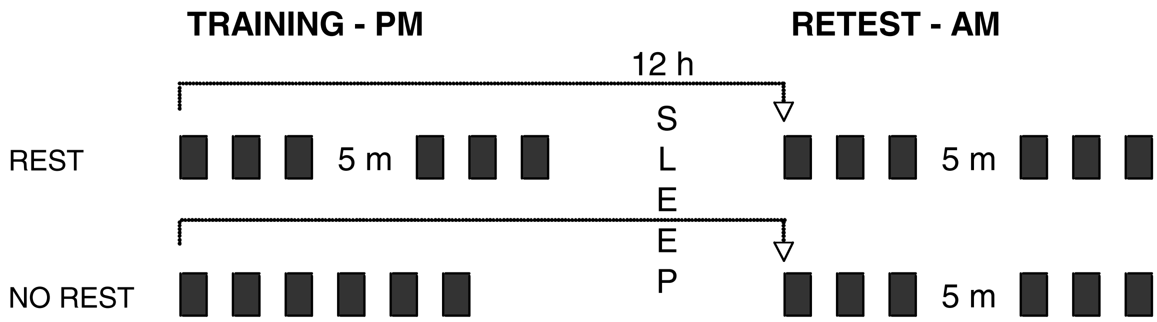

Figure 3: Design for Experiment 1. Participants trained on the test sequence for 6 30-second blocks (black boxes) alternating with 30-second pauses. For the Rest group, a 5-minute rest interval was introduced between Blocks 3 and 4. At retest, following a 12-hour interval that included sleep, participants practiced for six 30-second blocks with a 5-minute rest interval inserted between Blocks 3 and 4.

During 30-second pauses, I conversed casually with participants to minimize the possibility of mental rehearsal of the sequence. During each 5-minute rest interval, participants were permitted to leave the testing room momentarily to visit the water fountain and restroom. Once participants returned to the testing room, I conversed with them until the end of the 5-minute rest interval. Practice began immediately after the completion of the rest interval.

Retest

Each of the 26 participants was retested in the morning between the hours of 8:00 and 10:30 AM, approximately 12 ($\pm$1) hrs following his or her training session. At retest, participants repeated for 6 blocks the sequence learned at training. A 5-minute rest interval was inserted in place of the 30-second pause between Blocks 3 and 4 for all learners, regardless of whether they had rested for 5 minutes at training the evening before. The nature of the 5-minute rest interval was identical to that of training.

At the start of training and retest sessions participants reported the number of overnight hours slept. The Stanford Sleepiness Scale (Hoddes et al., 1973) was used as a self-report measure of participants' alertness. At the start of each session, participants reported their level of alertness on a scale of 1 to 7, with 1 representing "feeling active, vital, alert or wide awake" and 7 signifying "no longer fighting sleep, sleep onset soon, and having dream-like thoughts" (see Appendix B). The scale was previously used in studies examining memory consolidation of motor skills (Duke & Davis, 2006; Hotermans et al., 2006; Walker, Brakefield, Hobson et al., 2003; Walker, Brakefield, Seidman et al., 2003).

Experiment 2

Experiment 2 was designed to examine the effects of 5-minute rest intervals that appear early (prior to the transition from fast to slow learning) or late in training (after block to block improvements near asymptote). Data from this experiment were used to examine how the temporal position of a 5-minute rest interval affects changes in performance within a longer, 12-block, practice session. As in Experiment 1, data from this experiment were also used to compare the effects of rest intervals on post-practice, overnight memory consolidation processes.

Training

36 participants, randomly assigned one of three experimental conditions, practiced the test sequence, 2-5-3-4-2, for 12 30-second blocks at training, which took place in the evening between the hours of 8:00 and 10:30 PM. For the Early-Rest group (*N = 12)*, a 5-minute rest interval was introduced in place of the 30-second pause between Blocks 3 and 4; for the Late-Rest group (*N = 12)*, a 5-minute rest interval was introduced between Blocks 9 and 10. Participants in the No-Rest group (*N = 12)* practiced for 12 blocks without an extended rest interval (See Figure 4). The nature of the 5-minute rest interval in this experiment was identical to that of Experiment 1, in that during this time participants were free to leave the room for a few moments, and upon their return, casually conversed with me until the 5-minute interval had expired. Practice resumed immediately following the end of the extended rest interval.

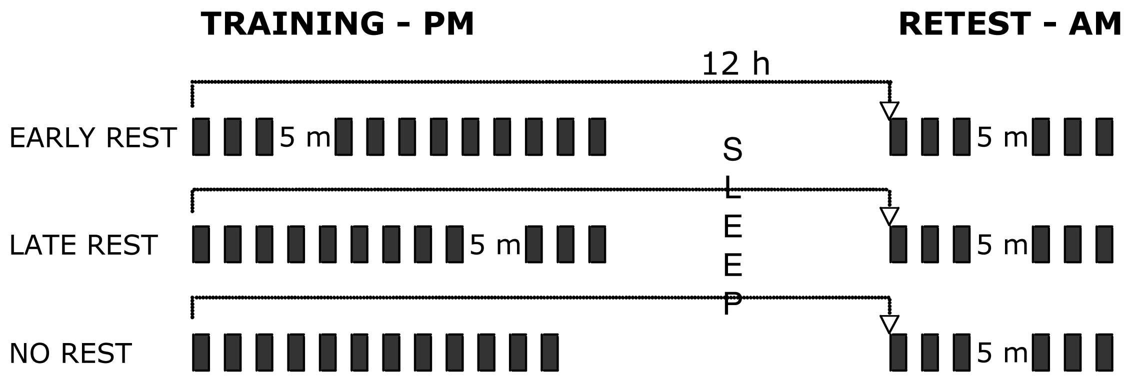

Figure 4: Design for Experiment 2. Participants trained on the target sequence for 12 30-second blocks (black boxes) alternating with 30-second pauses. For the Early-Rest and Late-Rest groups, a 5-minute rest interval was introduced in place of a 30-second pause following Block 3 or Block 9, respectively. At retest, following a 12-hour interval that included sleep, participants practiced for six 30-second blocks with a 5-minute rest interval inserted between Blocks 3 and 4.

Retest

Each participant was retested in the morning between the hours of 8:00 and 10:30 a.m., approximately 12 ($\pm$1) hrs following each participant's training session. At retest, all learners practiced the sequence for six 30-second blocks. A 5-minute rest was introduced in place of the 30-second pause between Blocks 3 and 4 for all participants.

As in Experiment 1, participants reported the number of overnight sleep hours and rated their alertness at the start of training and retest sessions.

DATA COLLECTION

MIDI data from training and retest sessions were recorded using Max/MSP Runtime, version 4.5.2 (Puckette & Zicarelli, 2004), installed on a 12-inch, Mac PowerBook computer. The version of Max/MSP used in the current study is identical to one programmed for previous studies using similar protocols (Davis, 2006; Duke & Davis, 2006). As well as recording and labeling each key press, the software program established whether the key press was correct and logged the total number of sequences (speed) and total number of errors (accuracy) per 30-second block.

DEPENDENT MEASURE OF SKILL PERFORMANCE

The number of correct key presses per 30-second block (CKP/B) was used as the dependent measure of skill performance in the current study. This measure is identical to the one used in similar protocols (Davis, 2006; Duke & Davis, 2006). In previous studies measuring the performance of finger-tapping skills, changes in performance are commonly reported using two separate variables: speed (number of sequences in a 30-second block) and accuracy (average number of errors per sequence in a 30-second block) (Hotermans et al., 2006; Kuriyama et al., 2004; Walker, Brakefield, Hobson et al., 2003; Walker, Brakefield, Seidman et al., 2003). Though the present study is modeled after these previous studies, the decision to use a single dependent measure somewhat different from previous measures stemmed from concerns that separate variables provide an unrealistic representation of overall performance. The relationship between speed and accuracy presents the likelihood that faster skill performance might come at the expense of less accurate execution and vice versa. Thus, improvement in one skill component, either speed or accuracy in this case, presents an inaccurate depiction of overall learning effects. In contrast, the dependent measure used in the present study combines *both* speed and accuracy. An improvement in speed, when accompanied by an increase in errors, is tempered when both skill components are combined in one measure. Similarly, an enhancement in speed, complemented by a decrease in errors, is augmented when speed and accuracy measures are combined. To determine CKP/B, the total number of errors per block was subtracted from the total number of key presses per block.

DATA ANALYSES

Statistical comparisons were made in terms of the changes in performance between 3-block triplets. Individual practice blocks were grouped in 3-block triplets; as Figure 5 shows, the 12 blocks of training and retest in Experiment 1 were grouped in four 3-block triplets. Likewise, the 18 blocks of training and retest in Experiment 2 were combined to form six 3-block triplets. The number of correct key presses per block was then averaged across each block triplet. Difference scores between successive block triplets were used to evaluate time-dependent learning among groups and over time. For example, mean difference scores between Block Triplets 1-2-3 and 4-5-6 of training in Experiment 1 were used to compare the rate of learning between learners in the Early-Rest group, who rested for 5 minutes between Blocks 3 and 4, and learners in the Late- and No-Rest groups, who did not rest for an extended rest period during this time. Similarly, changes in performance between Block Triplet 10-11-12 of training and Block Triplet 1-2-3 of retest in Experiment 2 were analyzed to examine the rate of improvements developing over a night of sleep.

Statistical analyses of the rates of change in performance between successive block triplets were carried out using a two-factor, repeated measures analysis of variance (ANOVA). Comparisons between skill learning, reported sleep hours, and sleepiness ratings were performed with Pearson's correlation coefficients.

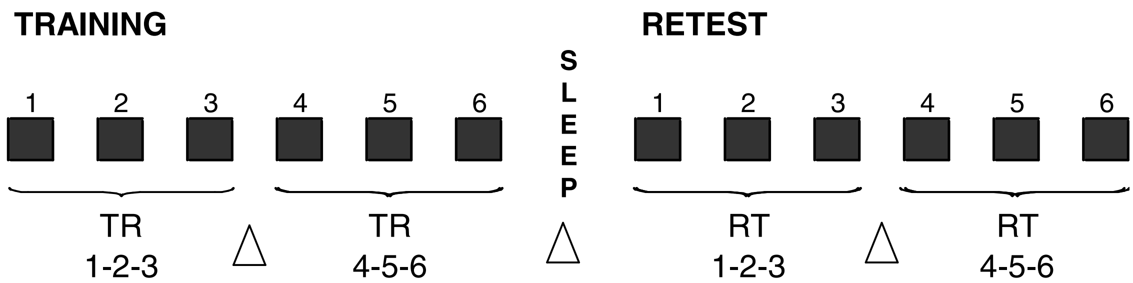

Figure 5. Groupings of 3-block triplets at training and retest in Experiment 1. The number of correct key presses per 30-second block (CKP/B) was averaged across 3 blocks. Difference scores between block triplets (triangles) were calculated and used for the statistical comparisons of within- and between-group learning. A similar protocol was used during the statistical analyses of data from Experiment 2.

Chapter 4: Results

In the present study, two experiments were designed for the purposes of examining behavioral changes in the skill performance of novices following 5-minute rest intervals. Results from each experiment were used to establish the extent to which processes that occur in the absence of practice, particularly across 5 minutes of rest, affect the learning of a new keyboard sequence. Data from Experiment 1 were used primarily to determine whether the presence of an extended rest interval within a 6-block training session affected the rate of learning within practice and across a subsequent night of sleep. Data from Experiment 2, in which participants trained on the new motor sequence for an extended, 12-block training session, were also used to study the effects of a 5-minute rest interval on within-session performance and post-training, sleep-based consolidation. Further, data from this experiment were used to determine whether the temporal placement of rest periods, either early or late in practice, influenced within- and between-session skill learning.

EXPERIMENT 1

Participant Data

Reported Sleep Hours

26 right-handed individuals (20F; *M* age = 19.35; *SD* = 1.41) participated in Experiment 1. Participants reported an average of 7.15 (*SD* = 1.60) hours of overnight sleep prior to training and 6.73 (*SD* = 0.82) hours of overnight sleep prior to retest. No

systematic differences were found among groups in terms of hours slept prior to training, $F(1, 24) = 0.53$, $p > .47$, or prior to retest, $F(1, 24) = 1.47$, $p > .24$. I found no relationship between hours slept prior to training and performance at the beginning of training, $r(24) = 0.12$, $p > .54$, or between hours slept and performance at the end of training, $r(24) = -.03$, $p > .87$. I found no relationship between hours slept prior to training and improvements between the beginning and end of training, $r(24) = -.33$, $p > .09$. No relationship, as well, was found between performance improvements at retest and reported sleep hours in the preceding night, $r(24) = -.07$, $p > .73$.

Reported Sleepiness Rating

The Stanford Sleepiness Scale was used as a self-report measure of participants' alertness. Sleepiness was ranked on a scale of 1 to 7, with 1 representing a high level of alertness and 7 representing a desire to fall asleep. Participants reported an average sleepiness rating of 2.56 ($SD = 0.78$) at training and 2.79 ($SD = 1.04$) at the start of retest. There were no significant differences among groups in terms of reported sleepiness at training, $F(1, 24) = 0.14$, $p > .71$, or at retest, $F(1, 24) = 1.53$, $p > .23$. I found no relationship between reported sleepiness rating and performance at the beginning of training, $r(24) = .18$, $p > .39$, or between sleepiness rating and performance at the end of training, $r(24) = .27$, $p > .19$. No relationship was found between sleepiness ratings and improvements between the beginning and end of training, $r(24) = -.20$, $p > .33$.

Performance Data

Performance of the sequential finger-tapping skill was assessed in terms of the mean number of correct key presses per 30-second block (CKP/B) as shown in Figure 6. Overall, there was a 70% increase in CKP/B for both groups across training, from 52.35 (*SE* = 4.09) at Block 1 to 89.19 (*SE* = 4.11) at Block 6. An additional increase of 18% was observed between the last block of training and last block of retest (105.31 CKP/B, SE = 5.12).

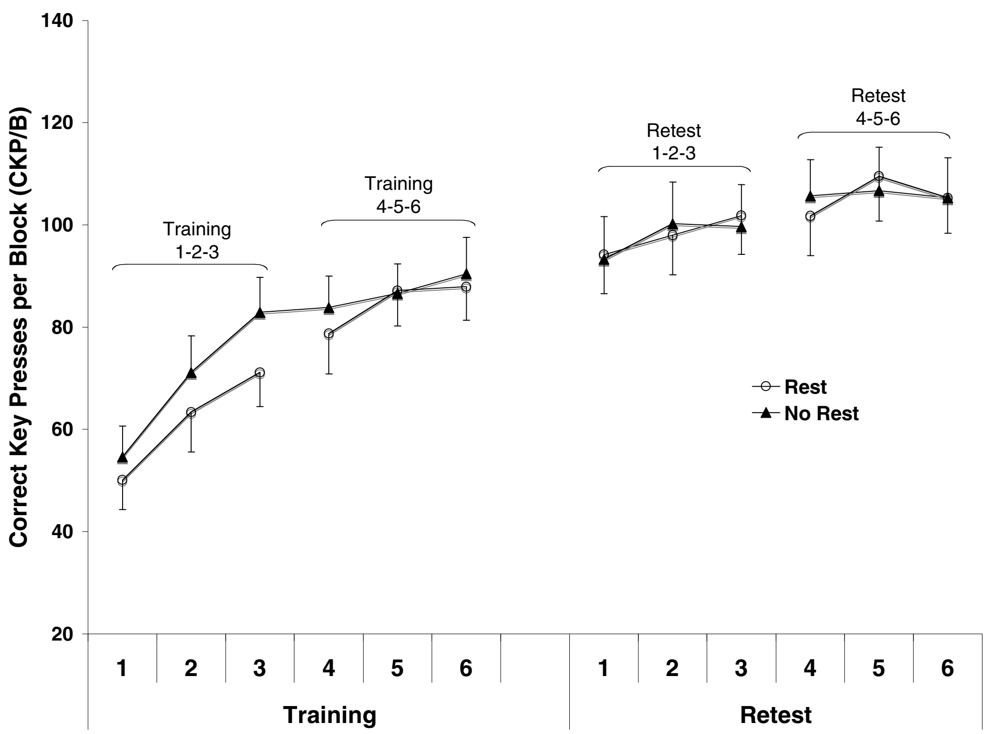

Figure 6. Performance, as measured by the number of correct key presses per block (CKP/B), at training and retest in Experiment 1. Error bars represent ± 1 standard error. 12 practice blocks were grouped into 4 block triplets to examine time-dependent learning across groups and over time.

Statistical comparisons were made in terms of 3-block triplets (i.e., the mean CKP/B across three consecutive blocks of practice). Figure 6 shows how the 12 practice blocks of training and retest were grouped into four triplets. After the mean CKP/B was determined for each block triplet (see Figure 7), I compared time-dependent learning within and between experimental groups by examining the rate at which performance changed between consecutive block triplets. Using a two-factor, repeated measures analysis of variance (ANOVA), I analyzed the mean difference scores (i.e., changes in performance) between successive block triplets. This analysis tested whether the rates of change varied across groups and over time.

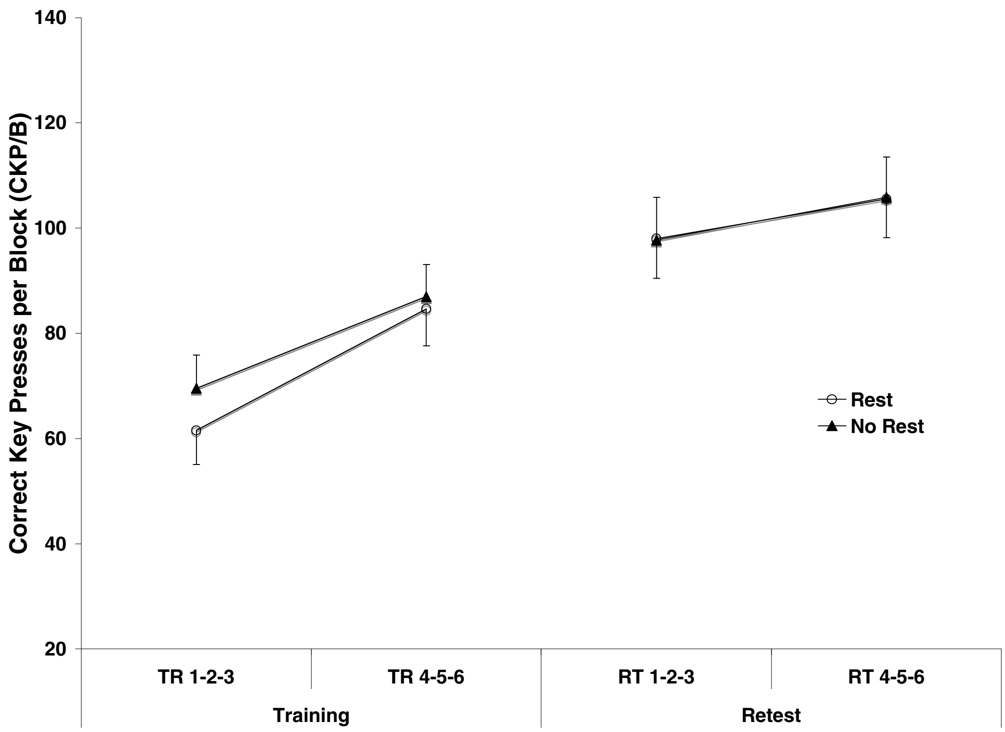

Figure 7. Performance, as measured by the mean number of correct key presses per block (CKP/B) for each 3-block triplet at training and retest in Experiment 1. Error bars represent ± 1 standard error.

Results show that the block triplet difference scores (i.e., the rates of change in performance) varied significantly across training and retest, $F(2, 48) = 7.43$, $p < .002$. I found no significant difference between groups when improvements were averaged across both sessions, $F(1, 24) = 2.85$, $p > .10$. Further, there was no interaction found between group and the rate of learning among block triplets, $F(2, 48) = 0.47$, $p < .63$ (see Figure 8), which indicates that the magnitude of improvements between a given pair of block triplets was not influenced by the presence of an extended rest interval. Results below are organized according to changes in performance across each of the three intervals separating consecutive block triplets (e.g., learning between Block Triplet 1-2-3 and Block Triplet 4-5-6).

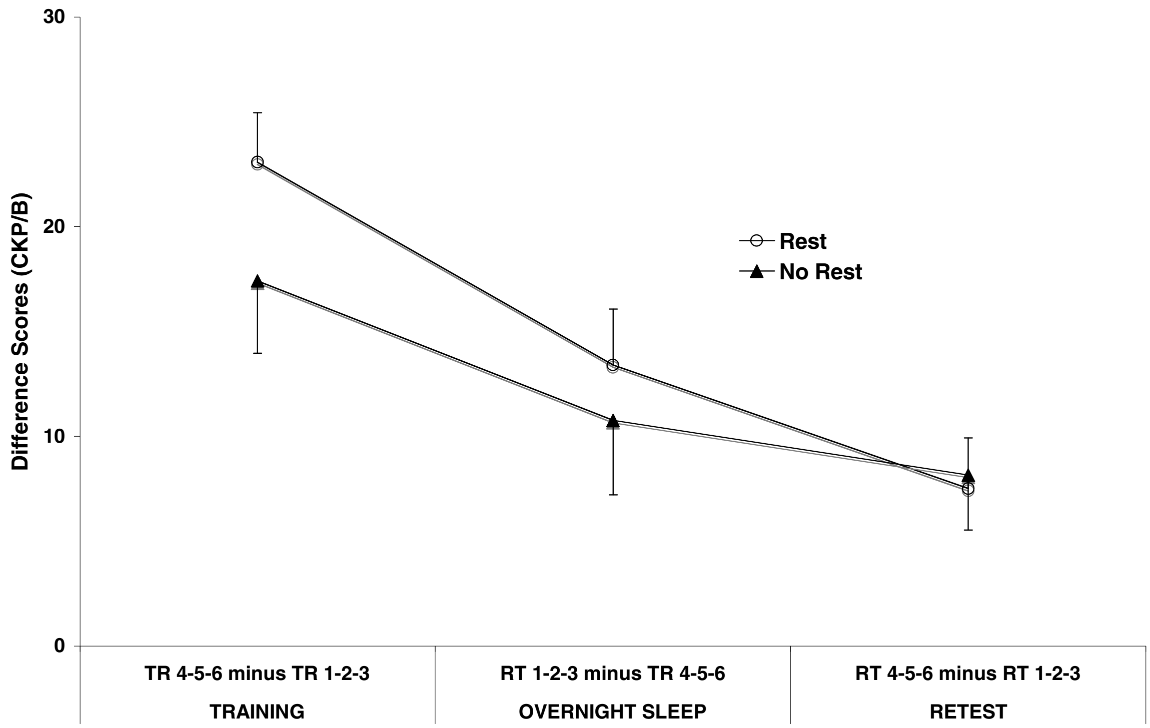

Figure 8. Mean difference scores between consecutive 3-block triplets at training and retest in Experiment 1. Error bars represent ± 1 standard error. Difference scores were determined by subtracting the mean CKP/B of a block triplet from the mean CKP/B of the subsequent block triplet.

Learning between Block Triplets 1-2-3 and 4-5-6 of Training

The performances of both groups indicate considerable increases in mean CKP/B between Block Triplets 1-2-3 and 4-5-6 of training. Learners in the No-Rest group improved an average of 17.41 CKP/B (*SE* = 3.44) (+25%) and learners in the Rest group had a mean increase in CKP/B of 23.08 (*SE* = 2.35) (+38%), though differences between both groups were found not to be significant.

Large incremental gains in skill learning observed early in practice, during which time learners adapt to new tasks, are consistently demonstrated with various motor tasks. As expected, both groups in this experiment showed rapid improvements in motor sequence performance across the first three blocks of training.

Learners in the No-Rest group attained a higher mean number of CKP/B by Block 3, 82.92 (SE = 6.84), than was obtained by the Rest group, 71.15 CKP/B (SE = 6.66) (see Figure 6). Changes in performance from Block 3 to Block 5 differed between groups; whereas performance improvements across this period slowed for learners in the No-Rest group, learners who rested for 5 minutes between Blocks 3 and 4 continued improving at a rate similar to that observed across the first three blocks of training. At Block 5, performance of the Rest group (87.15 CKP/B; SE = 6.93) reached that of the No-Rest group (86.62 CKP/B; SE = 5.81), with both groups achieving similar skill levels by the end of training. The patterns of improvement, though not significantly different between groups, seem of interest, and they provided the impetus for the design and implementation of Experiment 2.

Learning between Block Triplet 4-5-6 of Training and Block Triplet 1-2-3 of Retest

I examined learning across an overnight sleep interval of 12 hours by comparing the rates of change in performance between Block Triplet 4-5-6 of training and Block Triplet 1-2-3 of retest. Performance changes across a night of sleep indicate that learners in the No-Rest group improved an average of 10.77 CKP/B (SE = 3.55) (+12%), while those in the Rest group showed a mean increase of 13.41 CKP/B (SE = 2.66) (+16%).

Results indicating improvements across overnight sleep in this experiment are consistent with findings of a great deal of research examining sleep-based consolidation of motor memory. In this case, both experimental groups demonstrated comparable overnight improvements, regardless of whether learners had rested for 5 minutes during training.

Learning Between Block Triplets 1-2-3 and 4-5-6 of Retest

All learners rested for 5 minutes between the first and second halves of retest. I compared the rate of learning between Block Triplets 1-2-3 and 4-5-6 of retest. Learners in the No-Rest group increased an average of 8.16 CKP/B (*SE* = 2.61) (+8%), and those in the Rest group improved an average of 7.52 CKP/B (*SE* = 2.42) (+8%).

Summary

In Experiment 1, the presence of a 5-minute rest interval did not significantly affect improvements in skill performance of the keyboard sequence during training or at retest. Thus, results are inconsistent with data from the pilot experiment, which show that learners' performance is significantly improved immediately following a 5-minute rest interval. The course of skill improvements for both groups of learners in the present experiment, and in particular the trend toward greater skill enhancements developing across the extended rest period, however, are worthy of note and provide impetus for the design of Experiment 2.

EXPERIMENT 2

Participant Data

Reported Sleep Hours

36 right-handed individuals (20F; *M* age = 20.80; *SD* = 4.57) participated in Experiment 2. Participants reported an average of 6.99 (*SD* = 1.98) hours of overnight sleep prior to training and 6.44 (*SD* = 1.02) hours of sleep prior to retest. There were no systematic differences between groups in terms of hours slept prior to training, $F(2, 33) = 0.42$, $p > .66$, or prior to retest, $F(2, 33) = 0.72$, $p > .50$. I found no relationship between hours slept prior to training and performance at the beginning of training, $r(34) = .09$, $p > .61$, or between hours slept and performance at the end of training, $r(34) = -.06$, $p > .74$. There was no relationship between sleep prior to training and performance improvements from the beginning to the end of training, $r(34) = -.16$, $p > .34$. I also found no relationship between performance improvements observed at retest and hours slept in the preceding night, $r(34) = .20$, $p > .24$.

Reported Sleepiness Ratings

As in Experiment 1, participants rated their level of sleepiness at the start of each session using the Stanford Sleepiness Scale. Participants reported a mean sleepiness rating of 2.28 (*SD* = 0.91) at the start of training and 2.32 (*SD* = 0.98) at retest. No significant differences were found among experimental groups in terms of reported sleepiness ratings prior to training, $F(2, 33) = 1.49$, $p > .10$, or prior to retest, $F(2, 33) = 0.51$, $p > .60$. There was no relationship between sleepiness rating and performance at the beginning of training, $r(34) = .15$, $p > .37$, nor was there a relationship between sleepiness rating and performance at the end of training, $r(34) = .10$, $p > .55$. I also found no relationship between sleepiness rating and improvements made from the beginning to the end of training, $r(34) = -.02$, $p > .88$.

Performance Data

As in Experiment 1, performance of the keyboard sequence was assessed in terms of the mean number of correct key presses per 30-second block (CKP/B) as shown in Figure 9. As expected, there was an overall increase in CKP/B for all groups during training, from 36.81 ($SE = 2.69$) at Block 1 to 91.92 ($SE = 3.62$) at Block 12, a 149.7% improvement. There was an additional 16.9% increase between the last block of training and the last block of retest (107.44 CKP/B, $SE = 4.11$). Whereas all groups demonstrated an increase in CKP/B within and between sessions, discontinuities in learning curves of the Early- and Late-Rest groups were clearly observed following 5-minute rest intervals (e.g., at Block 4 for the Early-Rest group and at Block 10 for the Late-Rest group).

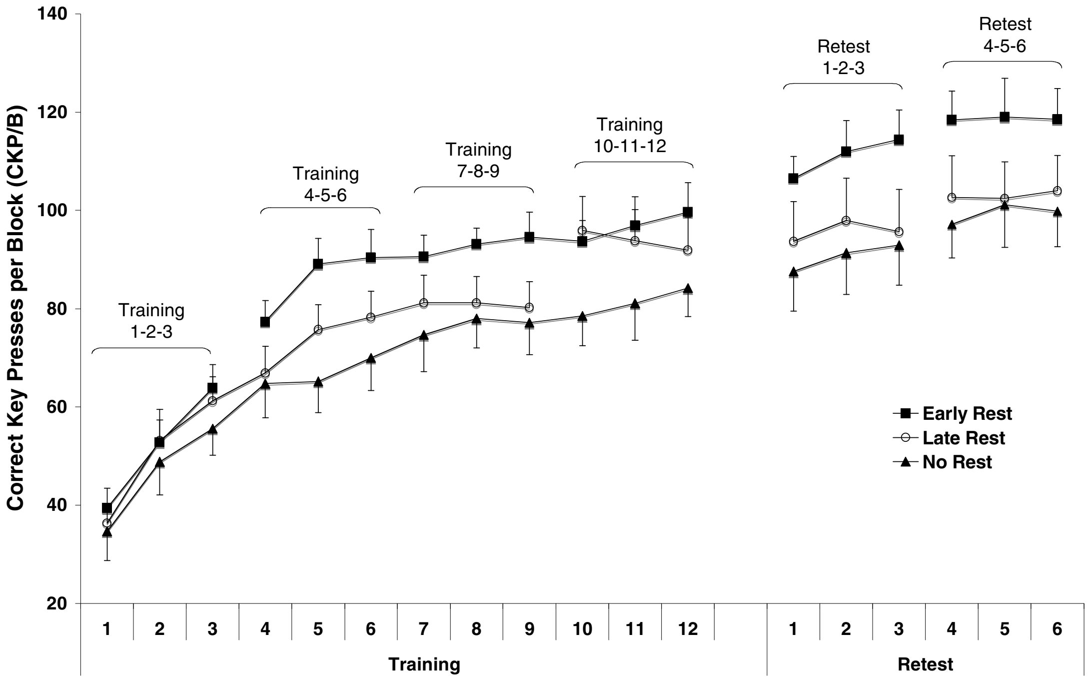

Figure 9. Performance, as measured by the number of correct key presses per block (CKP/B), across training and retest in Experiment 2. Error bars represent ± 1 standard error. 18 practice blocks were grouped in six 3-block triplets to compare time-dependent learning across groups and over time.

Statistical comparisons were made in terms of 3-block triplets. The 18 practice blocks of training and retest were combined to form six 3-block triplets. Figure 10 shows mean CKP/B per block triplet. As in Experiment 1, I analyzed mean difference scores (i.e., changes in performance) between successive block triplets using a two-factor, repeated measures analysis of variance (ANOVA).

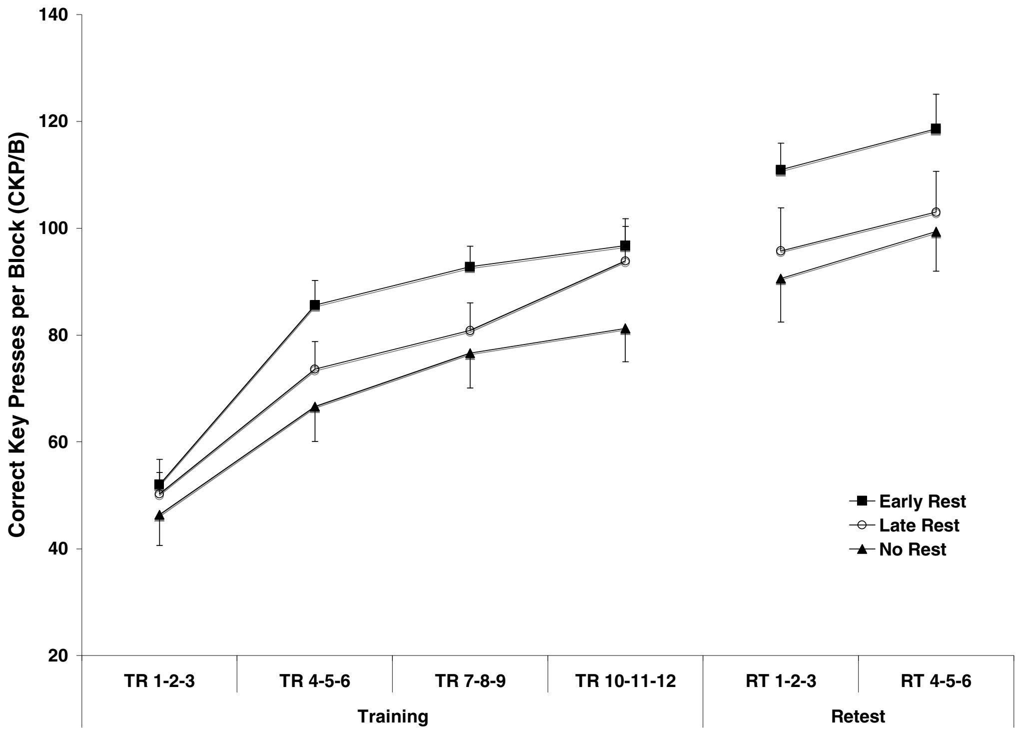

Figure 10. Performance, as measured by the mean number of correct key presses per block for 3-block triplets, at training and retest in Experiment 2. Error bars represent ± 1 standard error.

Results show that performance changes between block triplets varied considerably for all groups, $F(4,132) = 31.05$, $p < .001$. When averaged across training and retest, however, improvements between block triplets did not differ significantly among groups, $F(2, 33) = 2.26$, $p > .12$. More important was the significant interaction between groups and block triplet difference scores, $F(8,132) = 4.198$, $p < .001$ (see Figure 11). Results below are organized according to changes in performance across each of the five intervals separating consecutive block triplets.

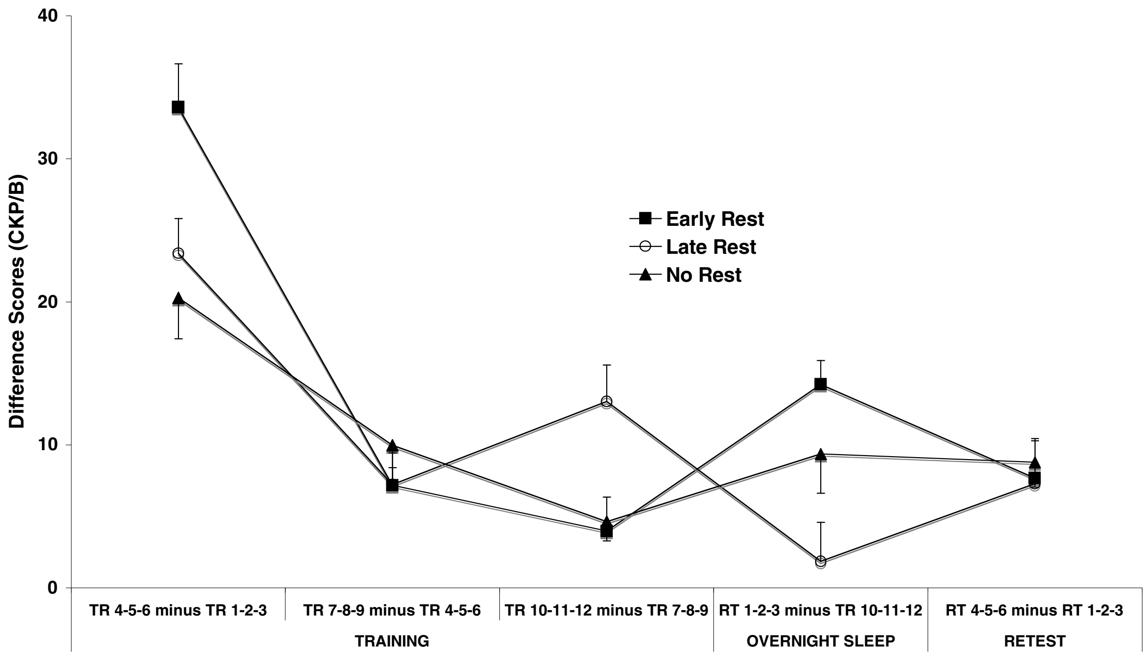

Figure 11. Mean difference scores between consecutive 3-block triplets at training and retest in Experiment 2. Error bars represent ± 1 standard error. Difference scores were determined by subtracting the mean CKP/B of a block triplet from the mean CKP/B of the subsequent block triplet.

Learning between Block Triplets 1-2-3 and 4-5-6 of Training

All groups demonstrated improvements in performance between Block Triplets 1-2-3 and 4-5-6 of training. Performance changes indicate that learners in the Late-Rest group had a mean increase in CKP/B of 23.39 (*SE* = 2.44) (+47%). Similarly, the No-Rest group increased an average of 20.28 CKP/B (*SE* = 2.86) (+44%). Improvements between the first and second block triplets were greatest, however, for the Early-Rest group, who rested for 5 minutes between Blocks 3 and 4; performance changes in this group indicated a mean increase of 33.61 CKP/B (*SE* = 3.03) (+65%).

The rate of change observed across Blocks 1 to 6 is representative of improvements typically made during the initial stage of skill acquisition. Throughout this "fast" phase of learning, learners are capable of making large gains in speed and accuracy as they adjust to new experiences. Clearly, the rates of learning across the first three blocks of practice were similar across all groups (see Figure 9). Differences between groups are apparent between Blocks 3 and 4, when the performance of learners who rested for 5 minutes show a greater degree of skill improvement. Hence, the Early-Rest group attained a higher number of CKP/B at Block 4 (77.33; *SD* = 4.34) as compared to performances of the Late- (66.92; *SD* = 5.40) and No-Rest groups (64.75; *SD* = 6.96). A similar rate of improvement by learners in the Early-Rest group was again observed between Blocks 4 and 5. Thus, a considerably greater difference between Block Triplets 1-2-3 and 4-5-6 by the Early-Rest group can be attributable to gains in performance developing across the 5-minute rest interval and continued improvements across the subsequent two blocks.

Learning between Block Triplets 4-5-6 and 7-8-9 of Training

Compared to changes made between Block Triplets 1-2-3- and 4-5-6 of training, the rate of skill learning between the Block Triplets 4-5-6 and 7-8-9 decelerated for all groups. Performances between the second and third block triplets of training improved an average of 7.17 CKP/B (*SE* = 2.28) (+8%) in the Early-Rest group, 7.22 CKP/B (*SE* = 1.20) (+10%) in the Late-Rest group, and 9.98 CKP/B (*SE* = 3.02) (+15%) in the No-Rest group.

Between Blocks 4 and 9, no discontinuities in the learning curves of any group were observed, nor were they expected since an extended rest interval was not introduced for any groups during this time. Slower rates of improvement following the initial period of large gains were observed between Blocks 4 and 9. Across this period, however, the Early-Rest group maintained a higher level of performance compared to those of the Late- and No-Rest groups. Recall that learners in the Early-Rest group obtained a greater mean number of CKP/B between Blocks 3 and 5 than did the Late- and No-Rest groups.

Learning between Block Triplets 7-8-9 and 10-11-12 of Training

With the exception of improvements made by the Late-Rest group, the rate of learning between Block Triplets 7-8-9 and 10-11-12 of training indicated further deceleration when compared to changes in performance occurring earlier in practice. More modest gains in skill performance are common in the later stages of initial practice. The introduction of a 5-minute rest interval between Blocks 9 and 10 for learners in the Late-Rest group, however, altered the course of expected improvements. Performance of this group increased by in 13.03 CKP/B (SE = 2.56) (+16%), as compared to an increase of only 3.97 CKP/B (SE = 2.39) (+4%) in the Early-Rest group, and 4.64 CKP/B (SE = 1.35) (+6%) in the No-Rest group.

Improvements between Blocks 9 and 10 by learners in the Late-Rest group—from 80.25 to 95.92 CKP/B, a 20% increase—is consistent with gains in performance typically observed during the first half of training. In fact, at Block 10, performance by the Late-Rest group (95.92 CKP/B; SD = 6.92) reached that of the Early-Rest group (93.67; SD = 4.37), which up until this point was highest among the three groups. The Late-Rest group did not show the same continued improvements observed in the Early-Rest group following a 5-minute rest interval (e.g., between Blocks 4 and 5), however. Instead, performance by the Late-Rest group, which was significantly improved after the 5-minute rest interval, decreased slightly between Blocks 10 and 12.

Learning between Block Triplet 10-11-12 of Training and Block Triplet 1-2-3 of Retest

Performances were compared between the last three blocks of training, Block Triplets 10-11-12, and first three blocks of retest, Block Triplets 1-2-3, to examine overnight, sleep-dependent learning across a 12-hour period. An increase in mean CKP/B of 14.22 (*SE* = 1.66) (+15%) was observed in the Early-Rest group. Over the same interval, the Late-Rest group improved by 1.86 CKP/B (*SE* = 2.71) (+2%) and the No-Rest group increased by 9.36 CKP/B (*SE* = 2.75) (+12%).

A great deal of research in motor memory consolidation reports significant enhancements in skill learning following a night of sleep. Results in this experiment are consistent with prior findings. No decrements in performance were observed, but changes in performance by the learners in the Late-Rest group showed only a limited amount of learning across an overnight sleep period.

Learning between Block Triplets 1-2-3 and 4-5-6 of Retest

Performance changes between Block Triplets 1-2-3 and 4-5-6 of retest were compared to examine the effects of a 5-minute rest interval on a recently-consolidated motor sequence. Recall that all learners rested for 5 minutes between Blocks 3 and 4 of this session. Changes observed between the Block Triplets 1-2-3 and 4-5-6 of retest were similar across groups: 7.67 CKP/B (*SE* = 2.77) (+7%) for the Early-Rest group; 7.28 CKP/B (*SE* = 3.01) (+8%) for the Late-Rest group; and 8.78 CKP/B (*SE* = 1.74) (+10%) for the No-Rest group. Overall, the changes in performance observed between Blocks 3 and 4, during which all learners rested for 5 minutes, was greater on average than changes made between all other blocks of retest, with the exception of that between Blocks 1 and 2.

Summary

In Experiment 2, the presence of a 5-minute rest interval, regardless of its temporal placement within a 12-block practice session, significantly enhanced performance of the keyboard sequence. However, continued performances subsequent to each of the 5-minute rest intervals, introduced either early or late in practice, differed from one another. Whereas learners continued to improve across the two pratice blocks following the 5-minute rest interval early in practice, learners who rested in the later stage of practice showed an immediate boost in performance following rest but did not continue to improve past this point. Also, learners who rested early in practice showed the greatest amount of performance changes following a night of sleep.

Enhanced performances following 5-minute rest intervals, particularly early in practice, provide support for results of the pilot study, which show significant enhancements in skill learning following extended rest intervals. Findings from the present experiment, however, are inconsistent with results of Experiment 1, which fail to show an interaction between the presence of a 5-minute rest interval and the magnitude of change in performance between consecutive block triplets. Differences in the course of improvements during training for learners in Experiment 1 do indicate a trend, however, toward a greater rate of performance changes over the 5-minute rest interval.

Chapter 5: Discussion

In the present study, I sought to examine the development of behavioral improvements in the learning of a keyboard sequence following 5-minute rest intervals. Enhancements in performance subsequent to rest periods comprising minutes have been observed in motor sequence learning (Davis, 2006; Hotermans et al., 2006), serial reaction time tasks (Heuer & Klein, 2003) and pursuit-rotor skills (Ammons, 1947; Denny, 1951; Eysenck & Frith, 1977; Kimble, 1952). In authentic learning contexts, as in the case of music practice, learners often interrupt skill repetition to rest from mental and physical fatigue. Though the effects of various time intervals between learning and retest on skill learning are reported at length, the influence of brief rest intervals on motor sequence learning has received less attention.

In an effort to clarify the role of 5-minute rest intervals in the learning of new motor sequences, three questions were posed at the start of this study. Those questions are:

1. Is a 5-minute rest interval sufficient time for off-line learning (neurophysical processes that occur in the absence of practice) to induce behavioral changes in performance?

2. Does the introduction of a 5-minute rest interval either early in practice, before performance is stabilized, or later in practice, after block to block

performance nears asymptote, differentially affect the development of behavioral changes during rest?

3. Does the offline learning that takes place across 5-minute rest intervals during practice affect the extent to which behavioral changes develop during subsequent, overnight memory consolidation?

Two experiments were designed to study the extent to which 5-minute rest intervals influence the learning of a simple keyboard sequence. Data from Experiment 1 were used primarily to determine whether the introduction of an extended rest interval in the middle of a 6-block training session affects within-session performance and the rate of learning across a subsequent night of sleep. Data from Experiment 2 were used to examine the effects of a 5-minute rest interval on performances over a longer, 12-block practice session as well as on behavioral changes that develop across sleep-based consolidation. Further, data from this experiment were used to determine the placement of rest within practice affects influences within- and between-session performance changes.

Following a summary of the results, I discuss outcomes in light of the research questions presented above. Results are organized according to the differential effects of rest on within-session performance, the relationship of rest to post-training, overnight memory consolidation processes, and the influence of rest on recently-consolidated skills. I also elaborate on the suspected bases for changes in performance in relation to 5-minute rest intervals.

SUMMARY OF RESULTS

Results show that, overall, performances of the keyboard sequence improved between the beginning of training and end of retest sessions. In both experiments, improvements generally were observed following episodes of extended rest, which comprised either 5-minute rest periods or 12-hour intervals that included overnight sleep.

In Experiment 1, learners who rested for 5 minutes midway through 6 blocks of training showed skill enhancements when practice resumed after rest, though the presence of the 5-minute rest period was not found to significantly affect performance changes during the experiment. Nevertheless, by the end of training, learners who rested between Blocks 3 and 4 were able to reach the level of performance of those in the No-Rest group, who had attained a greater mean CKP/B earlier in the session. Subsequently, rates of learning were similar across the remainder of training, over a night of sleep, and throughout retest for both groups.

In Experiment 2, learners showed considerable improvements in performance after 5-minute rest intervals, which were found to significantly influence the rate of performance changes across training and retest sessions. Enhancements were observed whether rest was introduced early in training, during which large gains in performance were already occurring, or later in practice, when performance improvements had stabilized. Though the magnitude of change across each 5-minute rest interval was comparable between groups, regardless of the placement of the extended rest, performance across succeeding blocks differed greatly from one another. At the end of training, learners who had rested for 5 minutes (either early or later in practice) attained a greater mean CKP/B than did learners in a third group, who had not rested for an extended interval. Further, the magnitude of changes across a night of sleep differed across groups; learners in the Early-Rest group showed the greatest improvement, followed closely by learners in the No-Rest group. Those in the Late-Rest group demonstrated only maintenance of performance levels between the end of training and beginning of retest. Additionally, groups in Experiments 1 and 2 showed improvements across a 5-minute rest interval introduced midway through retest.

EFFECTS OF REST INTERVALS ON WITHIN-SESSION PERFORMANCE

Early Rest Interval

A 5-minute rest interval was introduced after 3 blocks of practice to study the development of behavioral changes across rest periods that follow limited amounts of skill repetition. The amount of practice and the rate of learning prior to the extended rest period were taken into consideration when evaluating the influence of practice on off-line skill developments. Further, the implementation of a 5-minute rest period early on in practice allowed for the examination of its effects on subsequent performance.

Results show that when a rest period of 5 minutes is introduced near the beginning of practice, when significant gains in performance are already occurring, considerable improvements continue to develop across the rest interval. However, when learners do not have the opportunity to rest for an extended interval following three blocks of practice, performance improvements begin to decelerate, a common occurrence after the initial stage of skill repetition.

In Experiment 1, large gains in performance occurred across the first three blocks of training in both groups. Improvements continued across the 5-minute rest interval, between Blocks 3 and 4, and subsequently between Blocks 4 and 5 for learners in the Rest group. This rate of increase between Blocks 3 and 5, though not significant, was not observed in the No-Rest group, but did provide impetus for the implementation for Experiment 2.

In Experiment 2, learners in the Early-Rest group, who had demonstrated large, incremental gains across the first three blocks of practice, continued to show considerable improvements between Blocks 3 and 4. Conversely, learners who did not rest for an extended period at this time began to show a slowing in the rates of improvement between blocks. In the Early-Rest group, large improvements persisted between Blocks 4 and 5, immediately following the extended rest interval. Thus, the marked difference between performance of the Early-Rest group and the performances of other learners is attributable to the gains across an extended rest period and the continued improvements across the next inter-block interval. Though learners in the Early-Rest group attained a greater mean CKP/B by Block 5, the rate of change across the remainder of training was characteristic of a typical learning curve, in that the initial, large gains in skill gave way to more modest, incremental improvements.

The results have implications for the effectiveness of rest periods introduced early in practice. During initial skill repetition, considerable gains in performance are common as learners quickly acclimate to new experiences. Improvements during the *fast* phase of learning are usually characterized by increases in speed and decreases in errors. In the present study, learning curves demonstrate that the fast learning stage occurred roughly between Blocks 1 to 5 for all groups, after which rates of learning began to decelerate. Previous findings suggest that terminating practice during the fast stage of learning limits the consolidation-based enhancement of procedural memory.

The present study is the first to show that temporarily halting practice in its early stages for 5 minute has beneficial effects on the acquisition of a motor sequence; instead of a loss of learning across the rest interval, there is a boost in performance when practice resumes. This behavioral outcome indicates that neural processes, initially triggered by a limited amount of repetition, continue in the absence of practice. More importantly, the neural activity has the capacity to modify newly-acquired memory representations over 5 minutes of rest. Previous findings regarding the effects of limited practice on procedural learning show that neural activity triggered by a limited amount of practice may be insufficient to ensure the full benefits of overnight consolidation (Hauptmann et al., 2005). Results of this study, however, demonstrate that neural activity occurring immediately after practice is adequate to enhance performance when practice resumes after 5 minutes.

Further, learners who rested early in practice showed considerable improvements across two consecutive intervals—between Blocks 3 and 4 (during which they rested for 5 minutes) and again between Blocks 4 and 5—before rates of improvements began to decelerate. It is reasonable to assume that a rest of 5 minutes during early practice, when large gains in performance are occurring, may in fact, extend the period of fast learning. Therefore, resting early in practice may offer learners an advantage in that the capacity to make large improvements in skill performance is sustained for a longer period than would be observed without rest.

Late Rest Interval

In Experiment 2, a 5-minute rest interval was introduced between Blocks 9 and 10 to determine whether a greater amount of repetition preceding rest would influence the extent of behavioral changes following the rest interval. Again, I considered not just the amount of skill repetition preceding rest, but the rate of learning up to this point as well. Results show that up until Block 9, performances of learners in the Late-Rest group had progressed as expected; learning curves were characterized by large improvements early in training, followed by more modest gains across successive blocks. A considerable improvement in performance was observed, however, after the 5-minute rest interval. Current understanding of skill acquisition suggests that improvements of this magnitude in the later stages of practice are unusual. Slow learning is typified by a deceleration in the rate of improvement, whereas large gains in performance are generally associated with earlier skill practice. In fact, significant enhancements are rare once performance improvements begin to level off (Walker, 2005). Nonetheless, a 5-minute rest from practice, between Blocks 9 and 10, changed the expected course of improvements. Across this interval, learners showed marked enhancements typical of gains observed across earlier periods in training. Recall that learners in the Early-Rest group demonstrated considerable gains during the first 5 blocks of training. As a result, their performance surpassed that of other learners for the majority of the session. Learners who rested between Blocks 9 and 10 demonstrated sufficient improvements to reach performance of learners in the Early-Rest group.

These data demonstrate that rest periods of 5 minutes introduced in the later stages of practice yield significant improvements in skill performance as do extended rest intervals during early practice. Though the magnitudes of improvement across 5-minute rest periods were similar between the Early-Rest group and the Late-Rest group, the rates of learning in the blocks surrounding each of the rest periods were dramatically different from one another. Early in practice, learners had exhibited large incremental gains in performance when a 5-minute rest interval was introduced. Considerable improvements continued to develop during the extended rest period and over the next inter-block interval. Performance improvements across the latter half of practice, on the other hand, had leveled off before learners took a 5-minute break. Though performance subsequent to the rest period was markedly improved, no further gains were observed in the remaining blocks of practice or overnight. As a matter of fact, enhanced performance levels were barely maintained across the last three blocks of training in the Late-Rest group.

Results of the Late-Rest group are somewhat consistent with previous findings, which show that gains achieved after a period of rest from skill practice are rarely sustainable within a session (Eysenck & Frith, 1977; Hotermans et al., 2006). Rather, when practice resumes, performance regresses to that of pre-rest levels after a limited number of repetitions. In the present study, performance of the Late-Rest group did not revert to levels achieved before the 5-minute rest interval, though only 3 blocks of practice remained before the session was terminated. The amount of repetition afforded over 3 blocks may not have allowed for a complete return to pre-rest levels, although the slight decline in performance observed across the blocks may indicate that the effects of rest in this group were only temporary, perhaps as a result of the timing of the extended rest interval.

Interestingly, the temporary effects discussed above did not apply to learners in the Early-Rest group. Recall that performance by this group showed continued gains in the inter-block interval subsequent to the 5-minute rest. The theory that the behavioral effects observed following short rest periods diminish over subsequent repetitions may be only applicable to skill performances that have reached asymptotic levels. In other words, if rest is introduced during later stages of practice, during which large gains in performance are atypical, the beneficial effects of rest will rarely yield continued improvements past the initial boost. A saturation of performance gains late in practice may limit physical repetition from maintaining performance improvements. This is not the case with practice in the early stages of training, when learners can produce large gains in skill; introducing a rest interval during this time benefits learners because the capacity to make large improvements still exists when practice resumes.

EFFECTS OF REST INTERVALS ON BETWEEN-SESSION LEARNING

Recall that between-session changes in performance reflect mean difference scores between the last block triplet of training and first block triplet of retest, which were separated by a 12-hr, overnight interval that included sleep. Consistent with previous findings, results show that all groups, with the exception of the Late-Rest group in Experiment 2, demonstrated significant enhancements in performance when retested after a night of sleep.

There were differences in the magnitude of overnight improvements between experiments. These are not surprising and are most likely attributable to the amount of practice afforded to learners within each experiment (recall that Experiment 1 comprised 6 blocks of training as compared to a 12-block training session in Experiment 2). A stabilization of performance gains, reflected by the leveling off of incremental improvements, was observed when learners practiced for 12 blocks. Though not observed during a 6-block session, a leveling off in performance gains may reflect the establishment of new memory traces that continue to develop during off-line learning. Hauptmann and colleagues (2005) show that halting practice before performance stabilizes may limit memory consolidation enhancements during the first night of sleep. In support of this notion, Peigneux and colleagues (2003) report that post-training neural activations during periods of REM sleep are altered by the strength of the memory trace developed at practice. Although learners in Experiment 1, who repeated the new sequence for only 6 blocks, showed sleep-based enhancements at retest, one may assume that additional practice at training would have prompted further off-line learning.

One purpose of the present study was to investigate the relationship between performance improvements following 5-minute rest intervals and enhancements developing across post-training, overnight sleep. In a recent study, Hotermans and colleagues (2006) reported that the rates of change across 5- and 30-minute rest intervals are related to the magnitude of enhancements observed at retest 48 hours later. They suggest that performance improvements after short rest intervals reflect the capacity for the post-training enhancement of new skill memories (Hotermans et al., 2006). That is, when rest periods are introduced near the end of practice, the rates of change following a rest interval may indicate the extent to which behavioral improvements will develop across two nights of sleep.

Results from Experiment 1 show that learners improved an average of 8% across a night of sleep, regardless of whether they rested for 5 minutes during training. This may suggest that underlying processes developing across 5-minute rest intervals do not reflect the extent to which memory consolidation will progress over the hours following practice, and specifically across a night of sleep. Yet, results from Experiment 1 do not lead to a conclusive determination of how rest influences post-training memory consolidation processes. The 6 blocks of skill repetition may have been insufficient to bring about the potential effects of a 5-minute rest interval on between-session changes in performance.

In Experiment 2, however, differences in the amount of change across a night of sleep were observed between groups whose learners had practiced for 12 blocks at training. Thus, the opportunity for extended practice resulted in a leveling off of performance improvements, which was not observed among learners in Experiment 1. The stabilization of performance may be necessary before the effects of within-session rest periods are predictive of the extent of post-training, sleep-based enhancements.

As mentioned above, in Experiment 2, the rates of change across a night of sleep were different among groups. Learners in the Early-Rest group, who had attained a higher skill level by the end of training, showed the greatest increase in CKP/B at retest. Learners who did not rest for an extended period during training also showed improvements, though not as great as those of the Early-Rest group.

On the other hand, learners in the Late-Rest group only demonstrated slight improvements over a night of sleep. Limited, off-line enhancements for learners in the Late-Rest group could be attributed to the lack of sufficient practice between Blocks 10 and 12, after the 5-minute rest interval. After rest, learners in this group attained a considerably higher level of performance but were only afforded 3 blocks to repeat the new and improved skill level before practice was terminated. The likelihood exists that the limited number of task repetitions was not sufficient to establish the memory of the most recent skill level. Hotermans et al. (2006) may have recognized this likelihood when they sought to determine whether off-line improvements were related to behavioral outcomes following within-session, extended rest periods. Instead of comparing differences between the last blocks of training and the first blocks of retest, the authors analyzed the rate of learning between the last two blocks of training *prior* to 5- and 30-minute rest intervals and the first two blocks of retest. A significant relationship was found between improvements over brief rest periods and enhancements across a night of sleep. In the present study, when differences were compared between the Late-Rest group's last block triplet before the rest period (Block Triplet 7-8-9) and the first block triplet of retest, I observed overnight enhancements similar to those of the Early- and No-Rest groups. In fact, when analyzed in this manner, I found a strong correlation between improvements observed after rest and the magnitude of change across a night of sleep, $r(10) = .70$, $p < .01$.

Overall, these findings suggest that the placement of rest within a practice session affects the extent to which memory consolidation processes develop after the end of practice. First, rest introduced in the initial stages of practice offers learners an advantage, in that performance, which is significantly enhanced after the rest period, continues to show gains typical of fast learning across subsequent repetitions. A higher level of skill execution is reached early on and is maintained until the end of the session. Improved performances, as such, may indicate the likelihood for greater overnight enhancements. Second, boosts in performances following rest periods introduced later in practice, after which the rate of learning has leveled, may not *influence* subsequent memory consolidation processes. Instead, the post-rest behavioral effects may simply *predict* the extent to which performance may improve over a night of sleep.

EFFECTS OF REST INTERVALS ON RECENTLY-CONSOLIDATED SKILLS

Recall that all learners rested for 5 minutes halfway through their 6-block retest session, which took place in the morning, after a night of sleep. Groups in Experiments 1 and 2 showed improvements across the 5-minute rest interval during retest, regardless of whether they had rested at training. Results support the notion that recently-consolidated skills also benefit from rest intervals (Hotermans et al., 2006). In the present study, all groups rested for 5 minutes between Blocks 3 and 4 of retest and thus, no control group existed to compare performance improvements in the absence of a 5-minute rest interval. Nevertheless, that the rate of improvement, on average, was greater between Blocks 3 and 4, than between other blocks at retest, suggesting that the 5-minute rest interval was sufficient to affect subsequent performance.

Walker et al. (2003a) suggest that when consolidated memories are retrieved, they again are labile and susceptible to interference, requiring a period of reconsolidation. The reactivated memory of the sequence may represent a predisposition to further modifications during a 5-minute rest interval. I did not formally test for this hypothesis, however.

BASES FOR OFF-LINE LEARNING DURING REST INTERVALS

Several theories exist to explain the effects of rest intervals on skill learning. For example, it is proposed that *reminiscence*—improvements following brief periods of rest from skill practice—may simply represent the dissipation of physical or mental fatigue over rest intervals. Heuer and Klein (2003) show a significant improvement in a serial reaction time (SRT) task when practice resumes after a 3-minute rest period. The authors suggest that the break facilitates a release of fatigue-like effects developed during the repetition of the task. Their findings cannot be generalized to the present study for two reasons. First, training in Heuer and Klein comprised 1-minute practice blocks, each followed by 10 seconds of rest. In the present study, practiced alternated with rest pauses every 30 seconds. Data from previous studies examining the acquisition of finger-tapping skills, similar to the keyboard sequence used here, show that 30 seconds of rest is sufficient in combating physical and psychological fatigue accrued during repetition (Duke & Davis, 2006; Hotermans et al., 2006; Walker, Brakefield, Hobson et al., 2003). Second, Heuer and Klein introduced the 3-minute rest interval only before the last block of practice. In the present study, two groups of learners rested for 5-minutes after just 3 blocks of repetition; it is doubtful physical fatigue developed from the limited amount of practice. Therefore, a dissipation of fatigue in this instance may be unlikely to account for the performance enhancements observed following 5-minute rest intervals.

Another theory suggests that reminiscence is simply the result of the elimination of inhibitory effects amassed during practice (Ammons, 1947; Kimble, 1952). Repetition of a skill over time, without the availability of extended periods of rest, may interfere with the potential for further skill improvement. In these cases, a limitation of performance gains are not attributed to physical or mental fatigue, but are caused by inhibition, thought to intensify with each skill repetition and only dissipate during periods of rest.

It is reasonable to assume that the build up of inhibitory factors occurs most quickly over periods of continuous repetition, with practice intervals of increasing duration producing the most inhibition. Ammons (1947) shows that shorter periods of practice alternated with brief intervals of rest (as in the case of present study) allow for inhibitory effects to be eliminated more frequently. She reports that practice and rest alternating in 30-second cycles is superior to massed practiced followed by a 5-minute rest period. The present study extends these findings by demonstrating that distributed practice (separated by 30-second pauses) also benefits from the introduction of 5-minute rest intervals.

The theory of repetition-induced inhibition may extend the current understanding of development of skill learning over periods of practice. Initial performances of new skills are characterized by sizeable gains in performance followed by a deceleration of improvements. Inhibitory effects are shown to increase as a function of the amount of practice, regardless of the opportunity for rest (Kimble, 1952). Walker (2005) suggests that when performance nears asymptote, further repetition rarely yields additional significant gains and may even result in decreased performance. Practice beyond this point may, in fact, hinder the potential for further learning, which continues to develop only after practice has ceased. In these cases, rest allows for the removal of interfering stimuli present during practice, so that when repetition resumes, inhibitory effects are attenuated and performance is improved. But the return of skill to pre-rest levels shortly thereafter indicates that the potential for further learning is again constrained by inhibitory effects. The permanent attenuation of inhibition, thus, can only transpire when memory is stabilized and further enhanced during post-training memory consolidation processes.

The removal of inhibition by way of rest may be possible in the earliest stages of practice, as well. As observed in the present study, learners benefited from rest periods of 5-minutes after just three 30-second blocks of practice. Though considerable gains are common early in skill acquisition as learners adapt to new experiences, the break from skill repetition may allow for the dissipation of what little inhibition was amassed during a limited number of repetitions.

The conjecture that rest serves to reduce inhibitory effects that accumulate during practice points to the possible existence of a "pre-consolidation" stage of skill learning. Triggered by repetition, the neural processes occurring immediately after practice may serve to prepare memory representations for further stabilization and enhancement. Though the period may be transient, lasting perhaps for several minutes, it may function as the stage during which neural misfires or outlying signals, which represent errorful, uncharacteristic performances, are erased, or, in other words, "forgotten." What remains is an optimized memory trace ready for long-term consolidation. To date, no neurological studies exist to support this notion; however, several authors suggest that reminiscence may represent a the effects of an early stage of consolidation (Eysenck & Frith, 1977; Hotermans et al., 2006).

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

Consistent with previous findings, results from this study indicate that skill performance improves over periods of repetition as well as across intervals of rest. Results support recent behavioral data which indicate that rest intervals comprising minutes provide sufficient time for neural processes that develop in the absence of practice to yield enhancements in the subsequent performances of motor skills (Eysenck & Frith, 1977; Hotermans et al., 2006). Findings also suggest that the temporal placement of rest within a practice session has differential effects of subsequent motor sequence performance. This is the first study to document this phenomenon.

Undoubtedly, the influence of rest on motor sequence learning deserves further attention. Certainly, the effects of temporal position on performance were the most interesting results of this study and have implications for when learners implement rest during practice. These data, however, do not provide conclusive evidence as to the stability of reminiscence effects following rest intervals late in practice. In previous research, performance improvements following extended rest periods were found to return to pre-rest levels over continued repetition. Because learners who rested late in practice were only afforded three blocks of repetition following the 5-minute rest period, a return to performance levels attained before rest was not observed. However, a slight decline in performance over the last three blocks may suggest this to be the trend. Extending training to include additional practice blocks after rest periods introduced later in practice may allow for the further examination of reminiscence effects on performance that has been stabilized.

Findings of this study support those of Hotermans and colleagues (2006), who also found that performance of a motor sequence was significantly improved following 30 minutes of rest. Performance of the skill after 4 hours of rest, however, was similar to performance at the end of training. These results provide insight into the time course of off-line processes that are responsible for enhancements in skill following rest. Hottermans, et al. suggest that neural processes that support "boosts" in performance following rest may only be available within a 4-hour window. Studying how skills develop over varying intervals of rest (between 5 minutes and 4 hours) may provide a better understanding of the time course of neuroplastic modifications that occur in the absence of practice and their effects on subsequent motor performance. Likewise, examining the evolution of off-line learning across intervals shorter than 5 minutes may offer further insight into reminiscence effects. Recall that all participants in the present study rested for 30 seconds after each 30-second practice block. Initially included to combat physical and mental fatigue, these very brief rest intervals may provide sufficient time for neural processes to influence skill acquisition.

Motor learning is unquestionably central in the development of music performance skills. Gaining insight into how motor sequence learning develops will effectively lead to a better understanding of the cognitive processes that underlie skill learning and may explain how practice and rest affect the acquisition of music skills. Though traditionally absent from the motor learning literature, skill acquisition and retention among musicians has recently been addressed (Allen, 2007; Simmons, 2007; Simmons & Duke, 2006). Yet, there is a large discrepancy between the method in which skills are acquired in experimental contexts and how music skills are practiced in typical authentic settings.

Though the task used in the present study was performed on a musical instrument, generalizations of these findings to real-life music learning contexts are unwarranted at this time for several reasons. First, sound is an inherent component of music performance. Unlike other skills, physical movement in music produces concurrent auditory feedback. The sound variable was eliminated in the present study in an attempt to focus specifically on the development of motor skills. This is not to suggest that auditory and motor components are unrelated or processed separately during music learning. On the contrary, the two may indeed interact quite extensively during skill acquisition. For this reason, further study is necessary to determine the manner in which auditory processing interacts with motor skill learning during periods of practice and across intervals of rest.

Second, music performance calls for the execution of motor skills that are far more complex than the 5-note sequence used here. The development of learning over brief periods of rest has only been shown using simple skills that are brief and that can be acquired within one training session. More complex skills, such as those in music that frequently involve bimanual coordination or require more extensive periods of practice, for instance, may develop at different rates. Studying the effects of rest on the performance of tasks with greater complexity may lead to a more comprehensive understanding of how musicians acquire skills during periods of practice.

Third, the refinement of music skills often involves the balance of several performance variables, including note and rhythmic accuracy and speed. It is reasonable to assume that these components may develop at different rates over practice and overnight sleep intervals. Recent evidence suggests that this may, in fact, be true in the acquisition of keyboard sequences among musicians (Simmons & Duke, 2006). This finding may indicate that the variables of speed, accuracy, and temporal evenness, may also develop at different rates over shorter periods of rest from skill practice. Investigating the development of different music performance variables during practice and over rest may also provide further insight into the processes of motor skill learning in music settings.

Lastly, music is performed by individuals with widely varying levels of skill. This population includes children who are often beginning music lessons, adult amateurs, and experts who perform at the highest level of proficiency. Results regarding the development of motor skills in music practice contexts only begin to provide an understanding of how musicians learn. Much more extensive investigations of learning among varying populations is needed in order to fully develop a model of music learning.

Findings discussed above suggest that the learning of a simple motor sequence benefits from a combination of repetition, which triggers behavioral and neural modifications, and periods of rest, during which there is further processing of skill memory. Though behavioral data served as sole evidence of skill learning in this study, the behavioral outcomes were used to infer how off-line learning may generate changes in subsequent performance. Of course, a complete understanding of the time course of neural changes underlying motor sequence learning is not feasible through the examination of behavioral data alone. To date, there exists no neurological evidence to suggest that neural processes occurring in the absence of practice can trigger modifications in performance on short time scales. Investigations similar to those that supplement much of the behavioral evidence of memory consolidation over longer periods of time are needed to corroborate findings such as those obtained in the present study. Although further systematic examination of motor learning is necessary before results can be generalized to more complex sequence learning, to other forms of procedural skill acquisition, and to music practice, results presented here provide a valuable contribution to the current understanding of the development of motor skill learning.

Appendix A: Survey of Prospective Participants

1. Have you taken private or group lessons on an instrument or voice at any point in your life?

(circle) YES NO

If YES, please give the name of each instrument and indicate the year you began and the year you ended your lessons.

Instrument (or voice) ___________________ year began _____ year ended_____

Instrument (or voice) ___________________ year began _____ year ended ____

Instrument (or voice) ___________________ year began _____ year ended ____

2. Have you played or sung in an organized music ensemble (i.e., band, orchestra, choir) at any point in your life?

(circle) YES NO

If YES, please list the ensemble and indicate the year you began and the year you ended your participation.

Ensemble Type ___________________ year began _____ year ended ____

Ensemble Type ___________________ year began _____ year ended __________

Ensemble Type ___________________ year began _____ year ended __________

Are you interested in participating in a research study regarding skill acquisition and retention?
(You will be compensated in the amount of $10.00.) YES ____ NO ____
If yes, please provide your contact information below.

Name:_____________________________________

Email:_____________________________________

Thank you for your participation in this survey.
Carla M. Davis
Center for Music Learning, School of Music, The University of Texas at Austin

Appendix B: Stanford Sleepiness Scale

This is a quick way to assess how alert you are feeling. Each line below describes a level of alertness. Please choose which line fits your state of alertness right now.

Scale Rating	Degree of Sleepiness
1	Feeling active, vital, alert, or wide awake
2	Functioning at high levels, but not at peak; able to concentrate
3	Awake, but relaxed; responsive but not fully alert
4	Somewhat foggy, let down
5	Foggy; losing interest in remaining awake; slowed down
6	Sleepy, woozy, fighting sleep; prefer to lie down
7	No longer fighting sleep, sleep onset soon; having dream-like thoughts
X	Asleep

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